J. Indian Inst. Sci.
A Multidisciplinary Reviews Journal
ISSN: 0970-4140 Coden-JIISAD
© Indian Institute of Science 2022.

REVIEW ARTICLE

Materials for Indian Space Program: An Overview

S. V. S. Narayana Murty[*] *and S. C. Sharma*

Abstract | Materials are the backbone of any engineering structure and aerospace materials technologies are therefore closely guarded, in view of their dual use. Indian national space programmes such as the development of Polar and Geosynchronous satellite launch vehicles, communication and remote sensing satellites, recoverable space capsule, interplanetary missions such as Chandrayaan and Mangalyaan are symbols of the country's pride and owe their success largely to the dedicated efforts of material scientists towards development and indigenization of performance critical aerospace materials and products, over the years. The well-planned initiatives taken by ISRO in the early 1970s for the indigenous production of many of the structural and functional materials for the satellite launch vehicle programme were the earliest seeds sown which have yielded remarkable results in meeting the strategic material requirements of the present day, not only for space sector, but also in atomic energy and defense programs of India. Technology denials have in a way indirectly helped the country achieve self-reliance and in establishing large scale facilities required for meeting the materials demands of these strategic sectors. It is an undeniable fact that successfully meeting the critical requirements of all materials for Indian space programmes indigenously has been made possible through the dedicated efforts of teams which overcame several hurdles and challenges. This overview on the materials for Indian space program provides a glimpse of the efforts put to realize structural, thermo-structural and functional materials that are being used for various types of space missions. It presents the efforts in producing aerospace quality metallic materials like ultra-high strength maraging steels, aluminium, magnesium, titanium alloys, stainless steels, superalloys, powder metallurgical products and functional materials like electronic materials and thermal protection systems, in the past five decades. The overview culminates with discussion on the recent advances and future directions in aerospace materials and manufacturing.

Keywords: *Indian space program, Aerospace structural materials, Functional materials, Materials processing, Thermo-structural materials, Electronic materials*

1 Introduction

India, in her journey to space, reached the first major milestone in late 70 s with the launch of satellite launch vehicle (SLV-3) with a payload capability of 40 kg in low earth orbit (LEO). Beginning with augmented satellite launch vehicle (ASLV) and polar satellite launch vehicle (PSLV), her programs have entered the operational phase for providing telecommunication, meteorological and a host of other services to the

[1] *Vikram Sarabhai Space Centre, Trivandrum 695 022, India.*
**narayanamurty_susarla@vssc.gov.in*

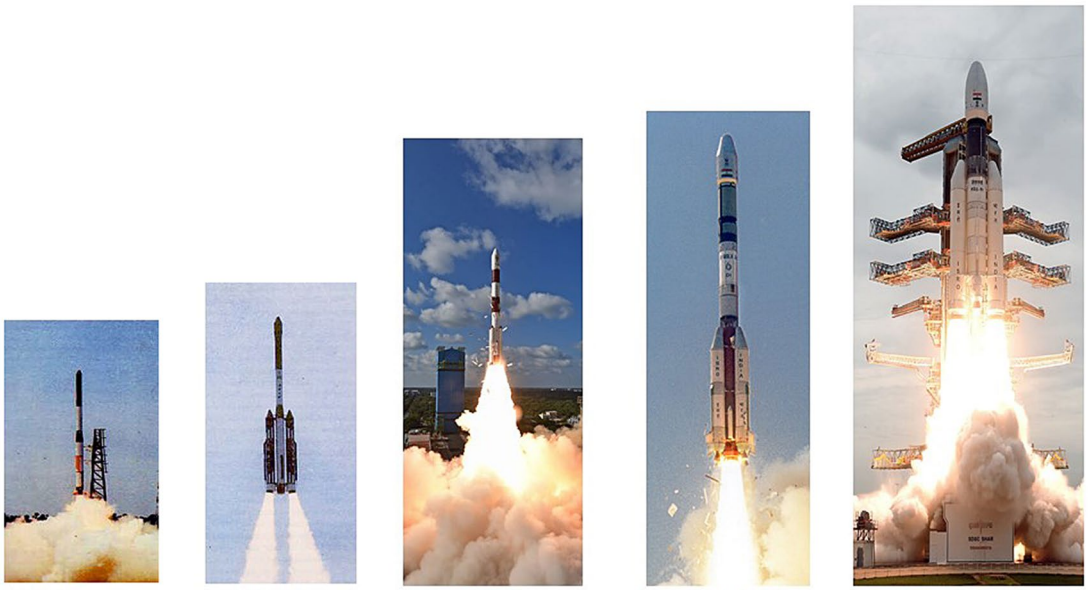

Figure 1: Progress in ISRO's satellite launch vehicle development programme during the past five decades with time lines. Both SLV-3 and ASLV used predominantly steels for their construction and are based on solid propellants. PSLV second stage and GSLV, both mark II and mark III versions extensively use aluminium alloys for earth-storable and cryogenic propellant tanks. The complexity of materials technologies increases from left to right.

nation through its geostationary satellite launch vehicle (GSLV), which has a payload capability of 2500 kg to geostationary transfer orbit (GTO) and GSLV-mkIII (4000 kg payload in GTO). Figure 1 shows the progress in ISRO's satellite launch vehicle development program during the past five decades with time lines. Most recently, ISRO has successfully conducted space capsule recovery experiment (SRE) and air breathing propulsion technology demonstrator making use of a scramjet engine demonstrating supersonic combustion in flight. It has also successfully accomplished Chandrayaan and Mangalyaan missions and is embarking on the prestigious Gaganyaan program to send humans to space and bring them back safely. Chandrayaan was the first Indian lunar probe launched by ISRO in 2008. Mangalyaan or the Mars Orbiter Mission (MOM) is the Indian space probe to mars launched in 2013. The salient technological features of advanced space missions in pipeline are: (1) propulsion based on air breathing/cryo/semi-cryo engines for RLVs (instead of the presently used combination of solid/liquid and cryo in PSLV and GSLV), (2) payload ratio (in LEO) of more than 2% for RLV (two stage to orbit or TSTO) and 1.50% for GSLV mkIII (instead of 0.9% for present GSLV) and (iii) service life of more than 15 years for RLVs (100 times of reuse). Development of reusable launch vehicles (RLVs) becomes imperative considering the need to: (1) bring down the launch cost by an order of magnitude compared to that of expendable vehicles, (2) improve mission success probability, (3) enable in-orbit servicing of space systems, retrieval of payloads for refurbishment and reuse, and re-fueling of satellites, (4) facilitate setting up of manufacturing bases for advanced materials and medicines in micro-gravity environment, and (5) reduce launch preparation time.

In order to keep pace with the advances taking place in the above space missions, the system-architecture needs to be more "material sensitive". Secondly, as ISRO`s on-the anvil space programs stand at par with current international efforts in this field, the role of so called

"reverse-engineering" in materials development tends to diminish. Lastly but most importantly, for strategic reasons, the realization of these materials through indigenous resources becomes absolutely essential. For its on-going projects, ISRO has built up a strong R&D and infrastructural base in the country for structural and functional materials such as maraging steels, aluminum, titanium and magnesium alloys, superalloys, hard and soft magnets, powder metallurgy (PM) products and materials for cryogenic applications. A set of thermal protection system (TPS) materials comprising SiC coated C–C composite, C-foam, silica tiles, and flexible surface insulation have been developed and some are in the advanced stage of development/realization.

Plausible scenario of the material sensitive architecture for RLVs poses formidable challenge of developing (1) high specific strength, stiffness and fatigue/damage tolerant structural and thermo-structural materials, (2) lighter and more durable TPS, (3) efficient cryogenic fluid containment materials, (4) special coatings and (5) smart materials/structures. Road map for realizing and successfully absorbing these advanced materials in Indian emerging space missions, includes an intensive R&D phase closely or concurrently followed by setting-up of infrastructural facilities. This paper, while recapitulating the salient strides already made for the realization of materials for space applications in the country, mainly focuses on the task which lies ahead for materials development for India's advanced space missions.

1.1 The Indian Space Program: Formative Years

A rocket can put an artificial satellite into earth's orbit, useful for remote sensing or communication purposes, when used for constructive purposes or carry a warhead and can be used as a missile for destructive purposes. Therefore, rocket technology is closely guarded by those nations which possess it. If India could, within six years of the launch of Sputnik-1, the first artificial satellite, venture into this field, it was due to the foresight and self-confidence of visionaries like Homi J Bhabha and Vikram A Sarabhai. When Nike-Apache, the first rocket from the Indian soil was launched from Trivandrum on 21st November 1963 at 18:25 IST, it heralded an era of space science and technology that brought laurels to the entire nation culminating with the western world taking a note of the Indian entry into the elite space club in the following years.

During the initial years of the establishment of Thumba Equatorial Rocket Launch Station (TERLS) at Trivandrum formed under the UN sponsorship, sounding rockets were launched to study the upper atmosphere. Thousands of these sounding rockets were launched from Thumba during 1970–1993, so much so that tourists visiting Trivandrum made sure that they were in town on a Wednesday, to watch rocket launch, the day on which they were launched.

1.2 Glorious Connection Between IISc and ISRO

As the department of metallurgy (presently renamed as Department of Materials Engineering) celebrates 75th year of its inception and as this special issue is being released to commemorate the seminal contributions of the Indian Institute of Science in general and Department of Materials Engineering in particular, it is apt to remember the connection between the two great institutions IISc and ISRO. It is amazing to note that the founding fathers of the ISRO's space program, Dr. Vikram Sarabhai, Prof. Satish Dhawan and Prof. Brahm Prakash, are related to IISc in many ways and played a key role in founding and nurturing the Indian space program. Dr. Vikram Sarabhai studied at IISc, Prof. Satish Dhawan, former chairman of ISRO was the director of IISc and Prof. Brahm Prakash, the first director of Vikram Sarabhai Space Centre, the lead centre for rocketry in India was the first Indian head of the department of metallurgy at the Indian Institute of Science. It is a matter of immense pride to note that this strong connection continues and became stronger and bigger over the years.

1.3 Growth of Indian Space Programme

Starting from the pencil rockets of RH75 (75 mm is the diameter of the rocket) for the study of the upper atmosphere in 1960's, ISRO matured gradually by first launching Rohini satellite (40 kg) by SLV-3; IRS class satellites (~1200 kg) into polar sun synchronous orbit by PSLV and GSAT class satellites (~2000 kg) in to geostationary orbit by GSLV. In the successful development of these launch vehicles, there were failures which were studied and analyzed systematically to overcome the causes. The details of integrated design for space transportation systems have been presented in[1] and readers who are interested in various deeper aspects of launch vehicle and related technologies can refer this book.

During the course of the development of these launch vehicles, several new technologies

Table 1: Material property requirements for various space applications.

Material property requirements	Space applications
High specific strength	Primary properties for structural materials
High specific stiffness	
High fracture toughness	
Good corrosion resistance	
Good damping capacity	
Ease of fabrication	
Compatibility with propellants, lining material etc	Motor cases/propellant tanks, especially liquid/cryogenic engines
Absence of ductile to brittle transition	For cryogenic engines
Low creep rate	For re-entry missions
High strength and low thermal conductivity at elevated temperatures	
High fatigue strength	
High dimensional stability Good thermal & electrical properties	Electronics packages & housings, in inertial systems etc
Good magnetic properties	For magnetic applications
(Residual induction, coercivity, maximum energy product, temp. coefficient of remanence etc.)	

were developed and demonstrated viz. strap-on-boosters (ASLV), liquid engine technology (PSLV) and cryogenic engine technology (GSLV and GSLV-mkIII). From the all solid propellant vehicle of SLV-3, ISRO has matured to use liquid engine technology in PSLV and subsequently cryogenic engine technology in GSLV and GSLV-mkIII, which have successfully launched several satellites. A powerful semi-cryogenic engine (2000 kN) development is under progress for future space missions. Several materials and related technologies were developed as a part of these launch vehicle projects. A cryogenic engine uses liquid hydrogen as fuel and liquid oxygen as oxidizer. A semi-cryogenic engine uses kerosene as fuel and liquid oxygen as oxidizer. Table 1 presents material property requirements for various space applications. Most of the materials used in these launch vehicles which were earlier imported were indigenized. Many in-house developed technologies have been transferred to Indian industries for production of flight hardware, leaving the research and development to ISRO centres. Large number of facilities were created in-house and outside, both in industries and R&D laboratories, catering to the needs of launch vehicles. With multiple launches of PSLV and GSLV/GSLV-mkIII year after year placing the indigenous and foreign satellites, the dream of Dr. Vikram Sarabhai has been made possible by the seeds sown by Prof. Brahm Prakash during the formative years of VSSC.

2 Criteria for Aerospace Material Selection

In order to achieve higher pay load performance of space transport systems, it is essential to reduce the dry mass of structural elements, as they do not contribute to the propulsive action during flight. There are essentially two types of loads that act on vehicle structures, the first one being internal loads such as those in the pressure vessels like solid rocket motor casings, propellant tanks, high pressure gas bottles and the second being external loads like air flow acting on the vehicle structures during flight. While the first part belongs to the domain of structural engineers on ensuring that the selection of materials and design of the pressure vessels meet the loading conditions with necessary margins, the latter is in the domain of aerodynamics and optimization of external loads. These inputs on the expected performance of structural members of launch vehicle decide material choice and the onus on producing the material with the desired specification meeting the quality control norms, henceforth is in the domain of the metallurgists. Details on the evolution of materials research for Indian space programmes are presented in an excellent book[2]. To give a glimpse in to the complexity of

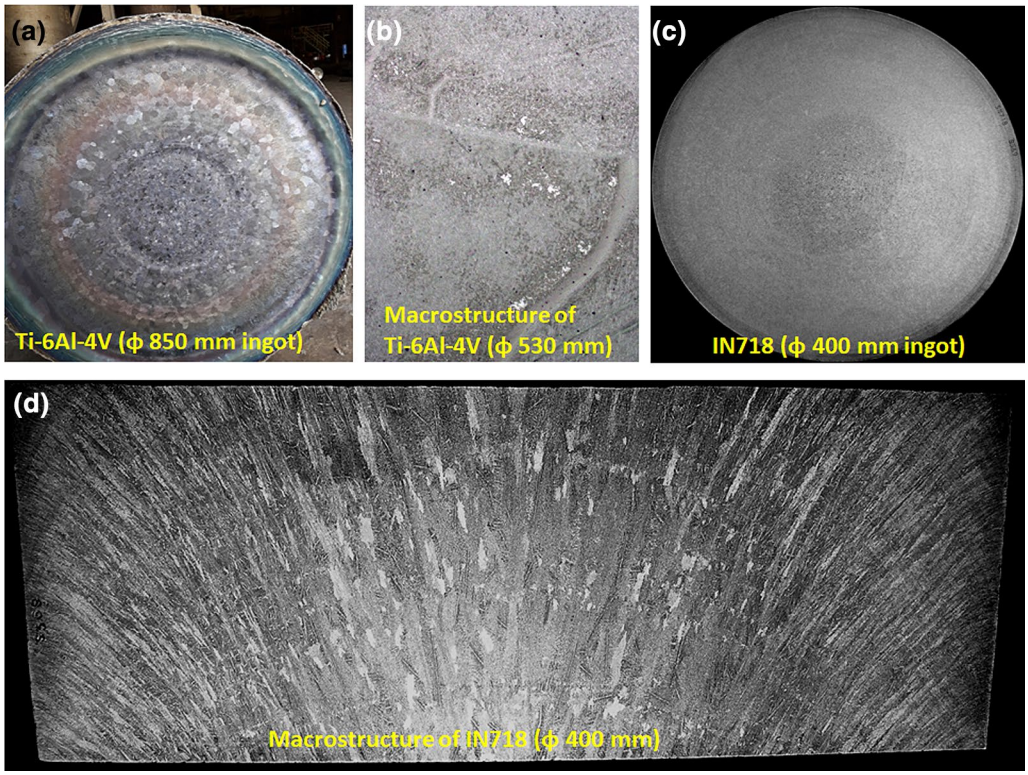

Figure 2: The journey for a material starts from the cast-house. **a** Photograph of a vacuum arc re-melted Ti-6Al-4 V ingot of ϕ850 mm ingot showing the coarse grain structure of the ingot; **b** macrostructure after cogging showing inhomogeneous structure and white spots; **c** macrostructure of ϕ400 mm Inconel alloy IN718 cogged ingot showing differential grain structure and **d** polished and etched section showing radial segregation pattern. The highly heterogeneous, as-cast microstructure needs to be converted to a homogeneous, near isotropic, wrought material with balanced strength-ductility-toughness amenable for performance critical, damage-tolerant, engineering applications.

metallurgical processing and where a material really starts its journey, Fig. 2 provides the macrostructures of as-cast, cast + homogenized and worked ingots.

It must be remembered that every kilogram of the weight saved in the upper structures of launch vehicle directly translates to the payload gained. This is the key driver in the selection of materials for launch vehicle structures. Therefore, the obvious choices are materials with high specific strength (ratio of strength of the material to the density) and high specific stiffness (ratio of the elastic modulus to density). It is also a misnomer that any improvement in strength of material reduces the weight of the structure directly; as the structure, must withstand the buckling loads and has therefore, a limiting thickness for a given structure. This implies that it is not the strength improvement alone that is the target of metallurgists to reduce the weight of a structure, it is the modulus of the material that decides the thickness and therefore, the dry mass. This is one reason why structural engineers prefer to choose the material systems like steels, titanium alloys, aluminum alloys in their maximum strength condition (peak aged tempers). The most important material selection criteria for space applications include high specific strength (strength to density ratio), high specific stiffness (Modulus to density ratio), design philosophy (yield based or fracture based design), service environment (compatibility with working fluids), temperature capability (superalloys, ablatives, thermal protections for high temperatures or cryogenic compatibility with cryogenic fluids), fabricability (ease of welding and Thermo-mechanical Processing), availability (Lead times in processing) and good corrosion protection methodologies for the selected materials. Availability of extensive test data on physical, mechanical and functional properties and proven track record along with reasonable cost, are other important considerations. Different types of structural and

thermo-structural materials for Indian Space Programs have been discussed.[3].

3 Materials for Solid Rocket Boosters

Sounding rockets and early launch vehicle programs of ISRO (SLV-3 and ASLV) used a high strength low alloy steel AFNOR 15CDV6 for the solid rocket motor casings. However, when the material for the large scale solid booster of PSLV was to be selected, the selection committee favored, 18% Ni, M-250 grade maraging steel. The solid rocket motor casing design is based on fracture mechanics approach and the 18 wt% Ni (M250 grade) maraging steel has several distinct characteristics that make it an ideal choice such as high strength coupled with excellent fracture toughness, good dimensional stability, ease of fabrication and simple heat treatment[4]. Table 2 presents the chemical composition of high strength steels for rocket motor casing applications.

Maraging steels are low carbon, iron-nickel martensitic steels which in presence of other alloying elements get strengthened by precipitation of a number of intermetallic compounds[5]. The distinct characteristics of this steel are high strength coupled with excellent toughness, good dimensional stability, ease of fabrication/welding and simple heat treatment[6–8]. The development activities for realizing the hardware from this steel for Indian space program included establishment of processing parameters (melting, forging, rolling, heat treatment etc.), evaluation of mechanical properties in different microstructural conditions and understanding the basic metallurgy of this ultrahigh strength steel. Maraging steel plates of size up to 10 m length × 2.5 m width × 7.8 mm thickness as well as 3.0 m diameter rings were successfully processed in large tonnage. Rocket motor cases for PSLV/GSLV/GSLV-MkIII fabricated out of this material are being regularly flown. Concerted efforts undertaken at VSSC/ISRO have led to the development of cobalt-free low nickel maraging steel[9] which has high specific strength/cost ratio and superior corrosion resistance.

The activity on maraging steels in VSSC started in the early 1970s using a button melting furnace. Since maraging steels belong to the class of ultra-high strength steels, they need to be processed with controlled chemistry, impurities and gas contents. Towards the end of 1970s, maraging steel was melted at tonnage level at M/s Mishra Dhatu Nigam Limited, Hyderabad and was used for successful fabrication and testing of a RH-300 rocket motor (300 mm diameter and 2.0 m in length). This material was proposed as a candidate material for the large PSLV solid rocket boosters of 2.8 M diameter. This material continues to be used in PSLV as well as GSLV and GSLV-mkIII till date. Maraging steel motor cases of 2.8 m diameter for PSLV and GSLV as well as 3.2 m diameter for GSLV mkIII are manufactured at Indian industries and are being flown regularly.

Several technical problems cropped up during the developmental phase and subsequent production phases[10,11]. These problems were solved through extensive experimental work at both VSSC and other industries. Some of the problems were low fracture toughness in ring rolled products[12] appearance of white streaks in X-ray radiography of large sized rings[10], HAZ II-parent material interface cracking[13], need for repair welding and local aging for fully aged segments, observations of stress corrosion cracking (SCC) and hydrogen embrittlement[14]. Solutions were provided to all these problems and the processing plans have been streamlined to meet the aerospace quality requirements.

At present, 18%Ni-M250 grade maraging steel required for ISRO programs is sourced from M/s Mishra Dhatu Nigam Limited, Hyderabad, in different forms. The steel is vacuum induction melted and vacuum arc re-melted in dedicated facilities set up for this purpose and the billets are rolled at Rourkela or Bhilai steel plant into the plates of about 8 mm thickness required for solid rocket motor casings. Large sized rings required for the fabrication of pressure vessels are ring rolled at M/s Bay Forge, Chennai in a ring rolling mill. Figure 3 shows maraging steel plate used for the fabrication of the solid motor booster cases, being rolled at Rourkela steel plant, Rourkela and rings required for the fabrication of rocket motor cases, getting ring rolled.

As Cobalt is one of the major alloying elements in maraging steels and as it is a strategic material, attempts have been made to replace Cobalt with other elements and the result is the development of Co-free maraging steels. In these steels, Co is replaced by Chromium along with an increase in Titanium content. To further reduce the cost of solid boosters, 15CDV6[15], a high strength-low alloy steel is modified by Niobium inoculation and increased carbon content to improve its strength and has been christened as 0.3%C-CrMoV (ESR) steel. Technologies have been developed to realize solid motor segments with this steel and have been qualified for use in flight[15–19]. Large diameter rocket motor casing made of this steel being oil quenched is shown in Fig. 3c. The

Table 2: Chemical composition of high strength steels for rocket motor casing applications.

Alloy	C	Mn	Si	Cr	Ni	Mo	V	Co	Others	S	P	Fe
.AFNOR 15CDV6	0.12–0.18	0.08–0.11	0.2 max	0.25–1.5	–	0.8–1.0	0.2–0.3	–	–	0.03 max	0.03 max	Rem.
Mod.0.3C CrMoV steel	0.27–0.31	0.8–1.0	0.2 max	1.25–1.5	–	0.8–1.0	0.2–0.3	–	0.08–0.12 Nb	0.015 max	0.02 max	Rem.
AISI 4130	0.28–0.33	0.4–0.6	0.15–0.3	0.8–1.1		0.15–0.25				0.04	0.035	Rem.
AISI 4340	0.38–0.43	0.6–0.8	0.20–0.35	0.7–0.9	1.65–2.0	0.2–0.3	–	–	–			Rem.
300M	0.40–0.46	0.65–0.9	1.45–1.80	0.7–0.95	1.65–2.0	0.30–0.45	0.05–0.10	–	–			Rem.
D6AC	0.42–0.48	0.6–0.9	0.15–0.30	0.9–1.2	0.4–0.7	0.9–1.1	0.05–0.1	–	–			Rem.
HY180	0.10–0.14	0.05–0.2	0.1 max	1.8–2.2	9.5–10.5	0.9–1.1	–	7.5–8.5	–			Rem.
AF1410	0.13–0.17	0.1 max	0.1 max	1.8–2.2	9.5–10.5	0.9–1.1	–	13.5–14.5	–			Rem.
AerMet100	0.21–0.27	0.1 max	–	2.5–3.3	11–12	1.0–1.3	–	13.3–13.5	–			Rem.
18Ni(250) Maraging	0.03 max	0.12 max	0.12 max	–	17–19	4.6–5.1	–	7–8.5	0.3–0.5 Tl 0.05–0.15 Al	0.01 max	0.01 max	Rem.
18Ni(250) Co-free Maraging	0.015 max	0.10 max	0.12 max	4.5–5.5	11.5–12.5	4.6–5.2	–	–	1.0–1.2 Ti 0.05–0.15 Al	0.01 max	0.01 max	Rem.
18Ni(300) Maraging	0.03 max	0.12 max	0.12 max	–	18–19	4.6–5.2	–	8–9.5	0.5–0.8 Ti 0.05–0.15 Al	0.01 max	0.01 max	Rem.
18Ni(350) Maraging	0.01 max	0.10 max	0.10 max	–	17–18	3.5–4.0	–	12–13	1.6–2.0 Ti 0.1–0.2 Al	0.01 max	0.01 max	Rem.

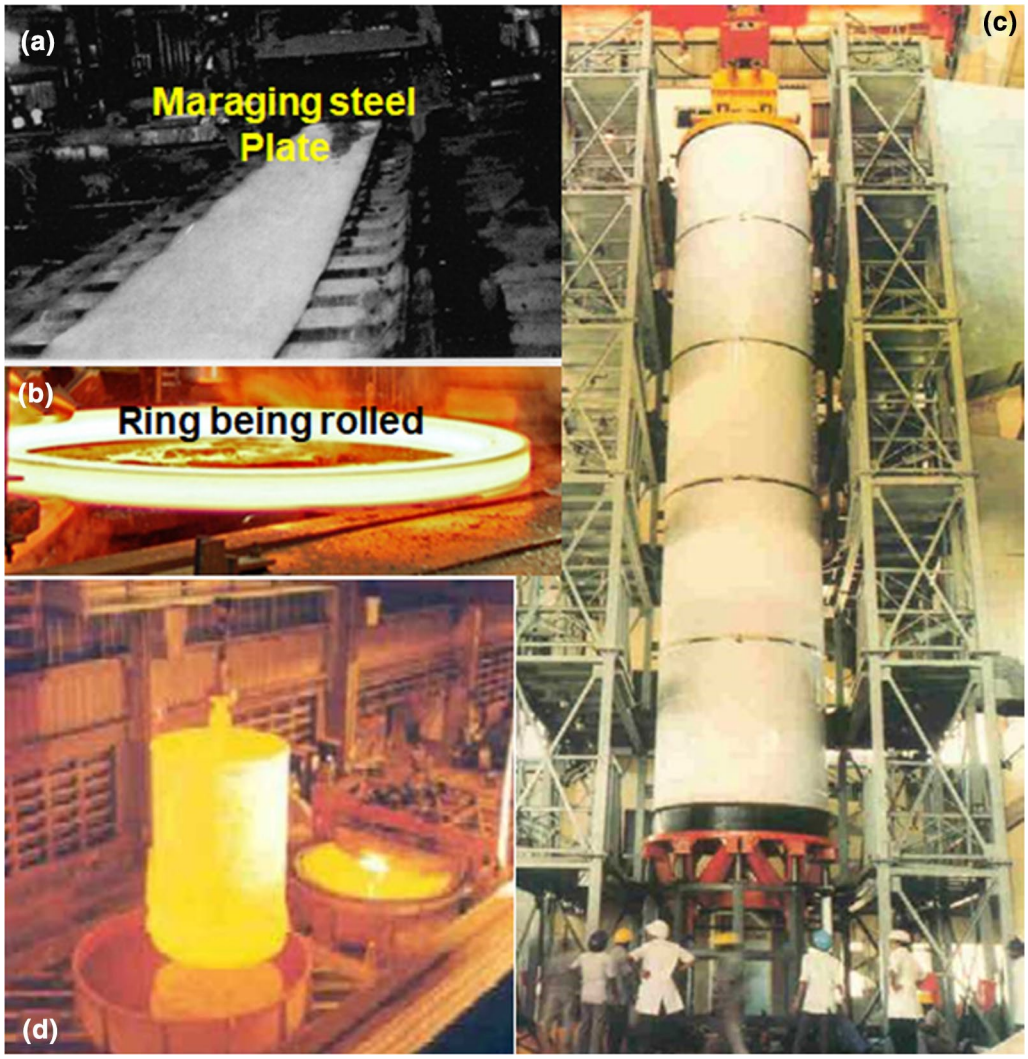

Figure 3: Maraging steel used for the fabrication of the solid motor booster cases, being rolled **a** at Rourkela steel plant, Rourkela; **b** rings required for the fabrication of rocket motor cases being ring rolled, **c** integration of the first stage of maraging steel motor case at SDSC-SHAR, Sriharikota, **d** large diameter rocket motor casing made of ESR grade 0.3C-CrMoV steel being oil quenched

integration of the first stage rocket booster of maraging steel at SDSC-SHAR, Sriharikota is presented in Fig. 3d. One development that is taking place currently is the development of flow forming technology for solid rocket booster cases using the ESR15CDV6 (0.3C-CrMoV steel). Once the technology is successfully established, it has potential to replace the present technology of maraging steel segments processed through rolling of plates and welding them to realize shells of rocket motors.

4 Aluminium Alloys for Earth Storable and Cryogenic Stages

The attractive characteristics of aluminum alloys such as high specific strength and specific modulus at ambient and cryogenic temperatures, ease of fabrication, high corrosion resistance, compatibility with liquid propellants make these alloys suitable for space applications[20]. Interstage structures, liquid fuel tankages, liquid engine components, cryogenic fuel tankages and heat shields are some of the critical components made of aluminum alloys. Table 3 presents aerospace aluminium alloys and their chemical composition and Table 4 presents their weldability for different structural applications.

It may be noted that the developmental rockets SLV-3 and ASLV used alloy steels and composites for different stages of solid rocket motors as they have 'all solid propellant' stages. When the PSLV was designed, the second stage (designated as PS2) consisted of a liquid stage

Table 3: Chemical composition of some aerospace aluminium alloys.

Alloy grade	Typical element content, wt.%										
	Zn	Mg	Cu	Mn	Cr	Zr	Fe	Si	Li	Ti	Al
AA 2219			6.3	0.3		0.2	0.3	0.2		0.1	Rem.
AA 2024		1.5	4.4	0.6			0.5	0.5			Rem.
AA 2124		1.5	4.1	0.6			0.3	0.2			Rem.
AA 2324		1.5	4.1	0.6			0.12	0.10			Rem.
AA 3003			0.1	1.0			0.7	0.6			Rem.
AA 5083		4.7	0.1	0.7	0.25		0.3	0.4		0.2	Rem.
AA 6061	0.2	1.0	0.2	0.1	0.35		0.3	0.6		0.1	Rem.
AA 7075	5.6	2.5	1.6		0.23		0.4	0.4			Rem.
AA 7150	6.4	2.35	2.2			0.1	0.15	0.12			Rem.
AA 7475	5.7	2.25	1.6		0.21		0.12	0.10			Rem.
AA 7055	8.0	2.05	2.3			0.1	0.15	0.1			Rem.
Al-Li 2091		1.5	2.1			0.1	0.30	0.20	2.0		Rem.
Al-Li 8090		0.9	1.3			0.1	0.30	0.20	2.4		Rem.
Al-Li 1441		0.9	1.7			0.1	0.3	0.1	1.9		Rem.
Al-Li 1460		0.05	2.8			0.1	0.12	0.1	2.2	0.06	Rem.
AA 2195	0.2	0.4	4.2			0.1	0.15	0.12	1.2		Rem.

Table 4: Weldability of aluminium alloys for structural applications.

Alloy	Weldable/non-weldable	Applications	0.2% proof stress (MPa)
Al-Cu (2219)	Weldable	Earth storable and cryogenic propellant tanks	360 (T87)
Al-Mn-Cu (3003)	Weldable	Lithium Ion battery cells case materials	185 (H18)
Al–Mg (5083)	Weldable	Aluminium alloy forgings in liquid engines	230 (H116)
Al–Mg-Si (6061, 6063)	Weldable	Materials for water tank of liquid engines	275 (T651)
Al-Zn-Mg (AFNOR 7020)	Weldable	Propellant tanks of earth storable stages	400 (T651)
Al-Cu-Li (2195)	Weldable	Light weight cryogenic propellant tanks	550 (T87)
Al-Cu-Mg-Si (2014)	Non-Weldable	Light alloy inter-stage structures of launch vehicles	410 (T651)
Al-Cu-Mg (2024)			450 (T8)
Al–Zn–Mg–Cu (7075 and 7055)	Non-Weldable	Forgings for control system components and components of liquid engine	500 (T651)
			600 (T651)

with a hypergolic combination of unsymmetrical dimethyl hydrazine (UDMH) as fuel and nitrogen tetroxide (N2O4) as oxidizer. A hypergolic fuel and oxidizer combination used in a rocket engine is one whose components spontaneously ignite, when they come into contact with each other. The propellant storage tanks for these are made of an Al-4.5Zn-1.5 Mg alloy (AFNOR7020) and were realized by TIG welding of rolled AFNOR7020 sheets and end rings/domes. Aluminium alloy AFNOR7020 has been in vogue in ISRO from the time of Viking engine technology transferred by Air Liquid, France and several PSLV and GSLV flights were successfully flown. However, this high strength aluminium alloy is prone to stress corrosion cracking[21] and was phased out after a leak in the propellant tank on the launch pad in an aborted GSLV flight. Henceforth, the material of construction of earth storable and cryogenic propellant tanks was changed to aluminium alloy, AA2219. Figure 4 shows the spectrum of aluminium alloys used in launch vehicles. Other important aluminium alloys that are widely used in launch

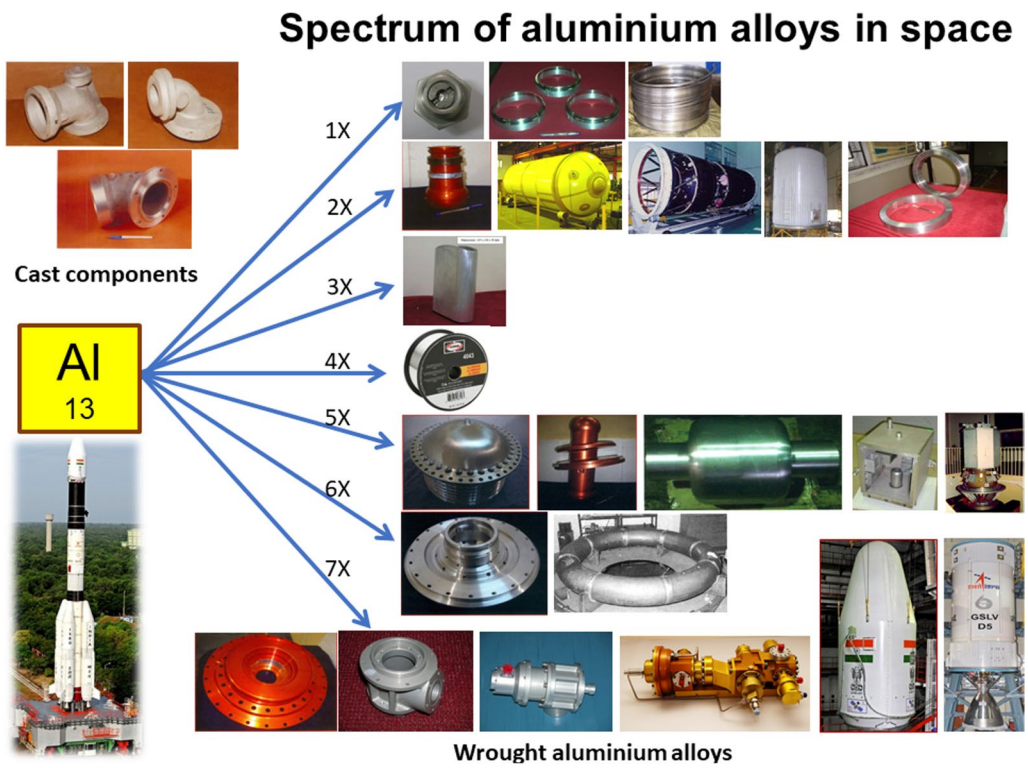

Figure 4: Spectrum of aluminium alloys used in space applications. Practically, every grade of wrought aluminium alloy is used based on their characteristics, for various applications. The age-hardenable aluminium alloys of 2XXX are used for earth-storable and cryogenic propellant tanks, 6XXX alloys for water tank of liquid engines and 7XXX series are used for engine components and heat shield. Aluminium alloy castings are used in liquid engines.

vehicles are AA2014 for inter stage structures, AA6061 for water tanks and AA7075 for various control system components of liquid engines[22].

To achieve complete self-reliance in high strength Al-alloys viz, AA2014, AA2219, AA7075 and AA 6061, ISRO undertook ambitious "Indigenization of Al-alloys" program in active collaboration with various industries in this field in the country. Under the program, DC cast billets/slabs, extruded products, rolled rings, forged rods, plates, sheets and tubes either have been realized or in the advanced stage of realization[23,24]. Clad AA2014 sheets (coated uniformly with AA1050 alloy) for protection against atmospheric corrosion have also been successfully developed for launch vehicles in the non-welded (riveted/bonded) structures. The quest to indigenize aerospace quality aluminium alloys required for ISRO's programs started in mid-1980s with the participation of Ordnance factory, Ambajhari and several hurdles were faced in meeting aerospace quality control. These limitations were successfully overcome with the establishment of a dedicated cast-house at Balco, Korba. Technology for melting and casting, meeting the critical aerospace specifications, is now available within the country and DC cast billets of these alloys are produced routinely at Hindalco-Almex at Aurangabad. The requirement of large sized rings are met through M/s Bay Forge, Chennai. Figure 5 shows the processing of large diameter aluminium alloy rings. Presently, aluminium alloys are the most critical materials for launch vehicle structures and the requirements are mostly met through indigenous sources except for large sized plates and sheets due to infrastructure constraints.

Conventional TIG welding process is used for the fabrication of earth-storable and cryogenic propellant tanks of PSLV and GSLV and GSLV-mkIII and these are fabricated out of aluminium alloy AA 2219[25]. With the establishment of friction stir welding technology as an attractive alternate fabrication process for increased productivity of aerospace hardware, ISRO has taken up this activity to demonstrate the FSW technology on the aluminium alloy flight hardware[26]. Extensive weld trials were conducted

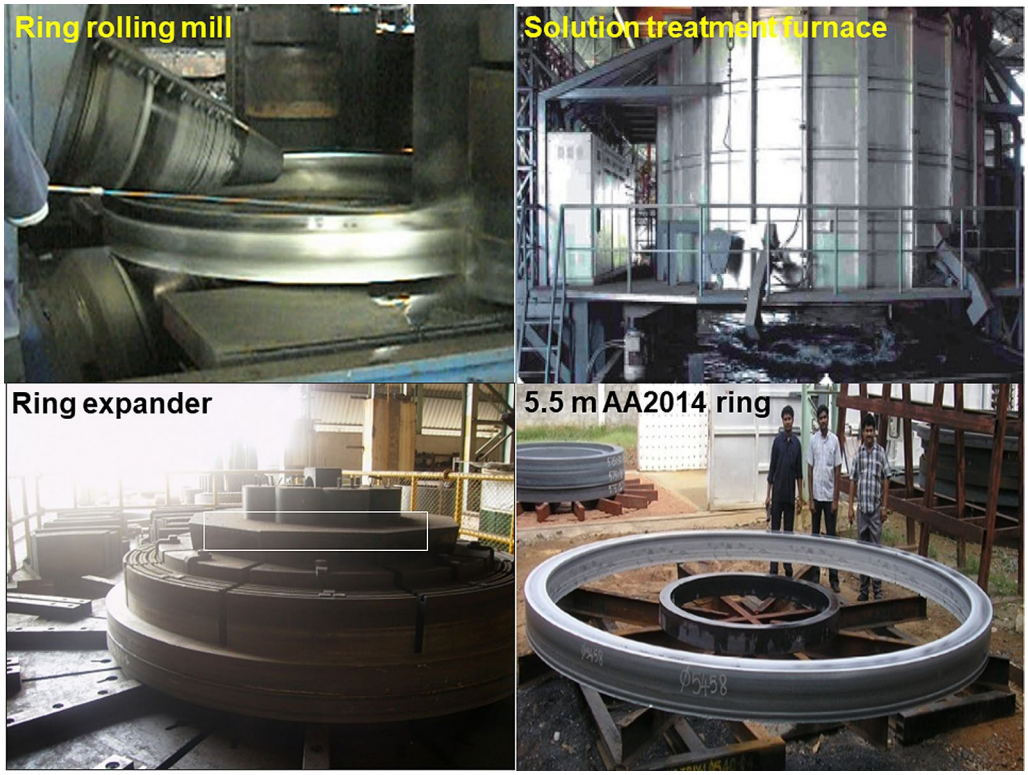

Figure 5: Photographs of **a** ring rolling mill capable of rolling large diameter (up to ϕ 5.5 m) rings used in the construction of aluminium alloy propellant tanks; **b** solution treatment furnace with a bottom quenching facility to meet the quench delay requirement for age-hardenable aluminium alloys; **c** ring expander for imparting the TX51 treatment to the rolled rings and **d** ϕ 5.5 M aluminium alloy AA2014 ring rolled ring.

and technology was demonstrated on long-seam weld joints of propellant tanks. The FSW welded propellent tanks have been successfully flown since PSLV-C39. Figure 6 shows the conventional and friction stir weld processes used in the construction of propellant tanks. Figure 7 shows the photographs of aluminium alloy honeycomb structures under fabrication of 5 M diameter heat shield panels under fabrication. Honeycomb structures are widely used for light weighting of aerospace structures.

The optical microstructures of aluminium alloy AA2219-T87 welded sheets using TIG, FSW and electron beam welding (EBW) presented in Fig. 6 show distinctly different macrostructural features. These differences have a strong bearing on the mechanical properties of the joints obtained. The low yield strength of aluminium alloy TIG welds is attributed to the presence of partially melted zone in in the fusion boundary. This low weld efficiency of AA2219 welds prompted researchers to look for lighter materials and welds with superior strength to reduce the dry mass of aerospace structures. This gap was filled by aluminium–lithium alloys[27]. The high lithium containing first and second generation alloys had issues related to the short transverse mechanical properties and corrosion resistance and could not provide the advantages expected. The third generation Al-Cu-Li alloys (AA2050, AA2195, AA2198) have successfully replaced the conventional AA2219 in many of the space applications, the most popular of which was the external tank of the space shuttle[28–34].

The higher specific strength and modulus combined with improved fracture toughness at ambient as well as cryogenic temperatures have attracted designers in successful application of third generation Al-Li alloy AA2195 in the Space Shuttle Super Lightweight External Tank (SLW ET) and AA 2297 for the intertank thrust panels of the SLW ET owing to its high elastic modulus and low density. These alloys are also used in many upcoming space transportation systems and aircraft in view of their higher specific strength and specific stiffness. Figure 8 shows the bright field transmission

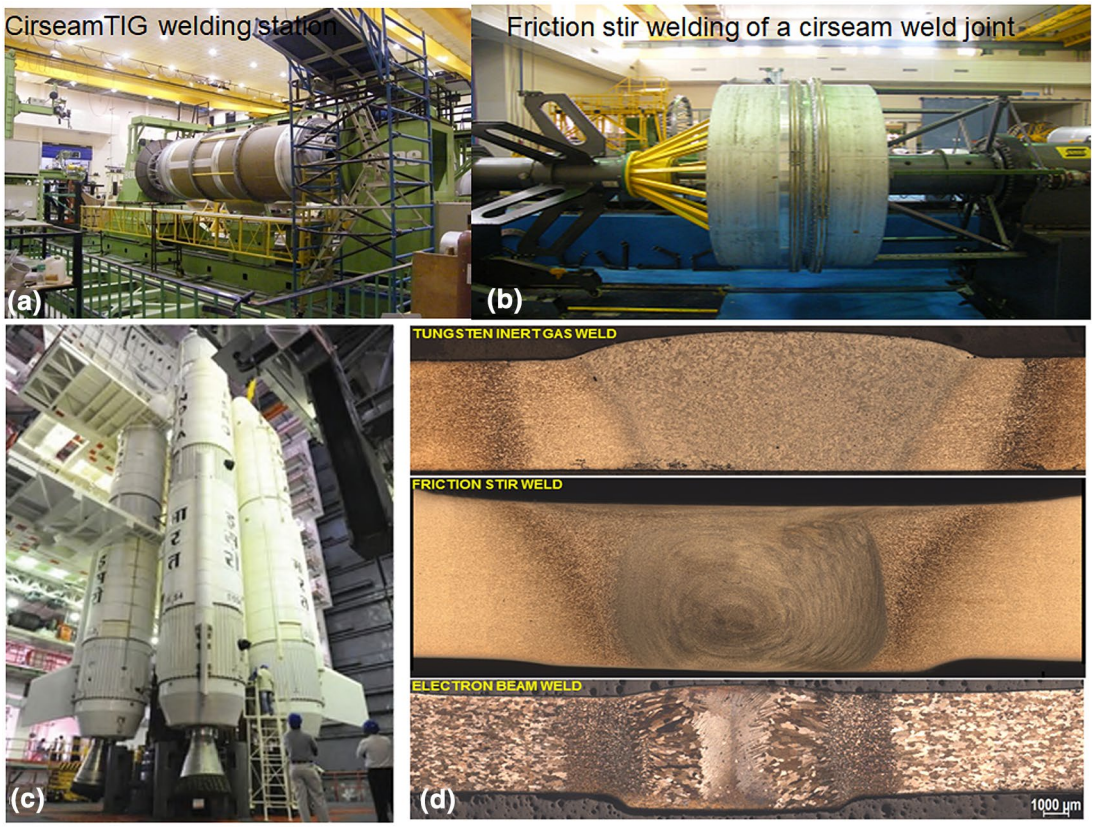

Figure 6: Photograph of **a** tungsten inert gas (TIG) welding station used for circumferential welding of propellant tanks; **b** Friction stir welding (FSW) of a circumferential weld joint of aluminium alloy propellant tanks; **c** strap-on L40 stages consisting of aluminium alloy propellant tanks under integration at SDSC-SHAR and **d** optical microstructures of aluminium alloy AA2219-T87 welded sheets using different welding processes viz. TIG, FSW and electron beam welding (EBW) showing distinctly different macrostructural features.

electron micrograph in the $<011>_{Al}$ projection for aluminium–lithium alloy AA2195 in T87 condition wherein the strengthening precipitates of few T_1 and θ' plates are marked by arrows[35]. Controlling the precipitate size, volume fraction and their distribution is the key in obtaining the desired properties in the advanced aluminium-copper-lithium alloys.

5 Titanium Alloys for Upper Stage Structures

In view of their high specific strength, excellent corrosion resistance, compatibility with propellants and good weldability, titanium alloys are choice of materials for aerospace applications[36,37]. Titanium alloys are essentially categorized into α, (α + β) and β alloys, based on the increasing phase fraction of β phase. The α and near-α titanium alloys are used for both cryogenic as well as for high-temperature/creep resistance applications up to 823 K. Lower diffusivity of alloying elements in α-phase results in superior creep resistance in these alloys. Near-α Ti alloys have fewer slip systems due to their hexagonally closed packed structure in comparison to (α + β) and near-β Ti alloys, which also contain β-phase with a body centered cubic structure. Commercially pure titanium is chosen for the fabrication of propellant tanks for satellites for long life cycle attributed to its excellent stress corrosion resistance[38,39]. Extra-low interstitial (ELI) grade Ti-5Al-2.5Sn is used for the fabrication of high pressure gas storage bottles for applications down to 20 K, in view of its superior fracture toughness. The two phase (α + β) Ti alloys find widespread applications from ambient to moderately high

Figure 7: Photographs of aluminium alloy honeycomb structures under fabrication (top) and (bottom) 5 m diameter heat shield panels under fabrication. Honeycomb structures are widely used for light-weighting of aerospace structures.

temperature. The microstructures of these alloys can be tailored to impart different α phase morphologies (lamellar, duplex and globular) through a combination of thermo-mechanical treatment and heat treatment[40]. The work horse (α + β) Ti alloy, Ti-6Al-4 V exhibits its room temperature strength up to 900 MPa in annealed condition and 1100 MPa in solution treated and aged (STA) condition. The β Ti alloys are characterized by high strength levels (~ 1400 MPa) and are used for structural parts such as skin panels, brackets and landing gears. Figure 9 presents the process flow for production of titanium alloy mill products. The sequence includes alloying addition and compaction of Titanium sponge to get compacted briquettes, plasma welding of briquettes to form the electrode, melting of electrode in a VAR melting furnace to obtain Titanium alloy ingots followed by forging in a hydraulic press. Table 5 presents the chemical composition, applicable international standards and T_β of a few Ti alloys used for space applications[36]. Table 6 presents various aerospace titanium alloys, their heat treatment cycle and typical mechanical properties[36]. Beta titanium alloys with improved mechanical properties and titanium aluminides for high temperature applications are under development[41–44].

High pressure spherical gas bottles carrying inert gases are used for pressurization during/pre-flight operations where titanium alloy Ti-6Al-4V is used (200, 400 and 600 mm diameter for different applications) in annealed condition. These spherical gas bottles are processed by closed die hammer forging to hemi-spherical shapes and are electron beam welded. Even though closed die forging is used, machining operation is essential to realize the final contour with varying thickness as per the stress analysis, resulting in significant material wastage. Therefore, processing technology based on hot forming of plates was also developed to realize such hemi-spherical shapes and one such important requirement was a propellant tank for a spacecraft with a diameter of 1200 mm. This requirement was successfully met with material in solution treated and aged condition, in view of its higher strength in this material

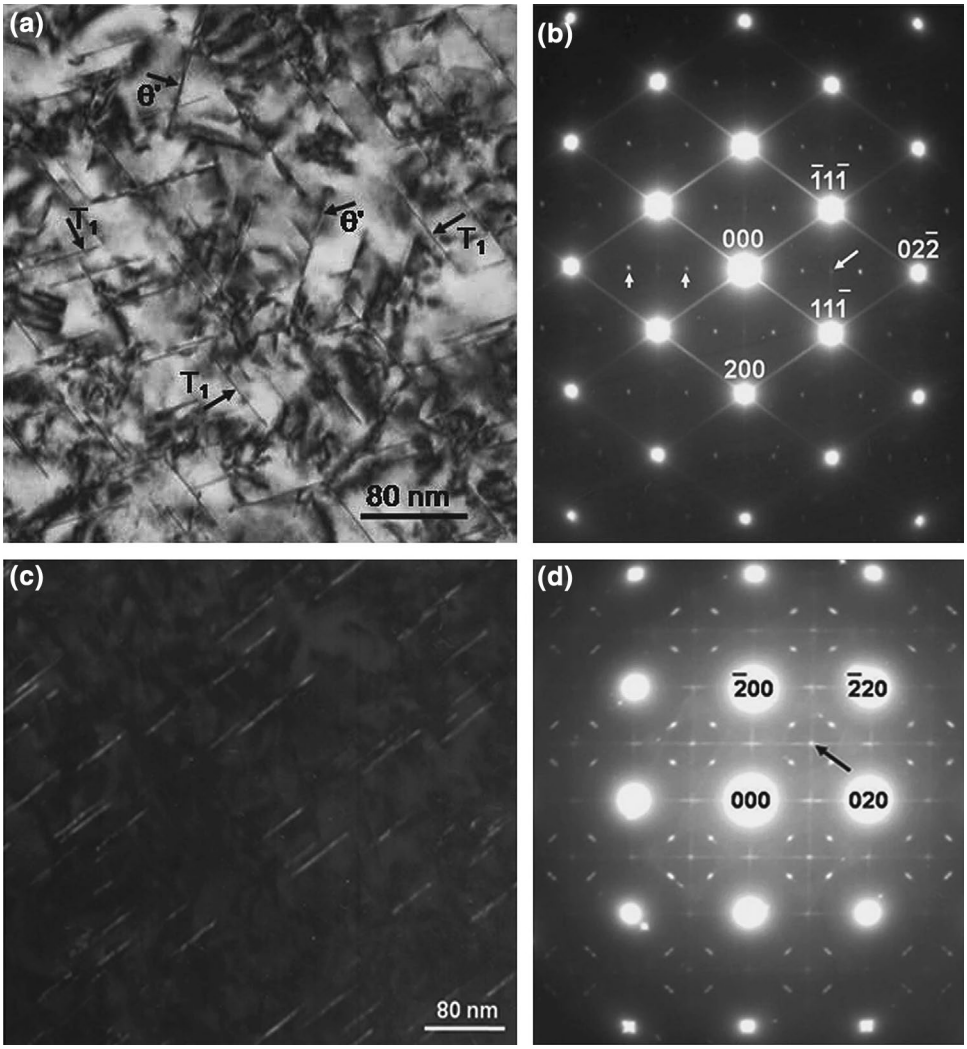

Figure 8: **a** BF Transmission electron micrograph in the $<011>_{Al}$ projection for aluminium–lithium alloy AA2195 in T87 condition wherein few T_1 and θ' plates are marked by arrows. **b** SAEDP in $<011>_{Al}$ projection corresponding to **a** showing streaks along $<111>_{Al}$ directions due to the presence of thin plates of T_1 on $\{111\}_{Al}$ planes, and streaks along $<200>_{Al}$ direction through matrix Al reflections as well as $\{110\}_{\theta'}$ spots [one marked by a long arrow] due to θ' plates forming on $\{100\}_{Al}$ planes. One set of diffraction spots at $1/3<220>_{Al}$ and $2/3<220>_{Al}$ positions due to T_1 are further marked by a pair of short arrows. **c** CDF image using one set of streaks along $<111>$ Al direction in **b** showing thin T_1 plates. **d** SAEDP in the $<001>_{Al}$ projection showing streaks along $<200>_{Al}$ directions through the matrix Al reflections and through the {011}θ' spots (one marked by an arrow) due to θ' plates forming on $\{100\}_{Al}$ planes. $1/3<220>_{Al}$ and $2/3<220>$ Al diffraction spots due to T_1 are further observed.

condition. The development of high-pressure gas bottles through plate forming route has resulted in a cost saving of almost Rs. 2.7 lakhs/bottle compared to that of forging route. Titanium alloy lined composite gas bottles (Kevlar and Carbon fibre), which have more than 50% weight advantage over all-titanium gas bottles, have also been successfully developed and are being flown. Figure 10 shows various titanium alloy mill products and fabricated components used for space applications.

Thermomechanical processing of titanium alloys is very challenging. An example of embrittlement of Ti-5Al-2.5Sn alloy that has

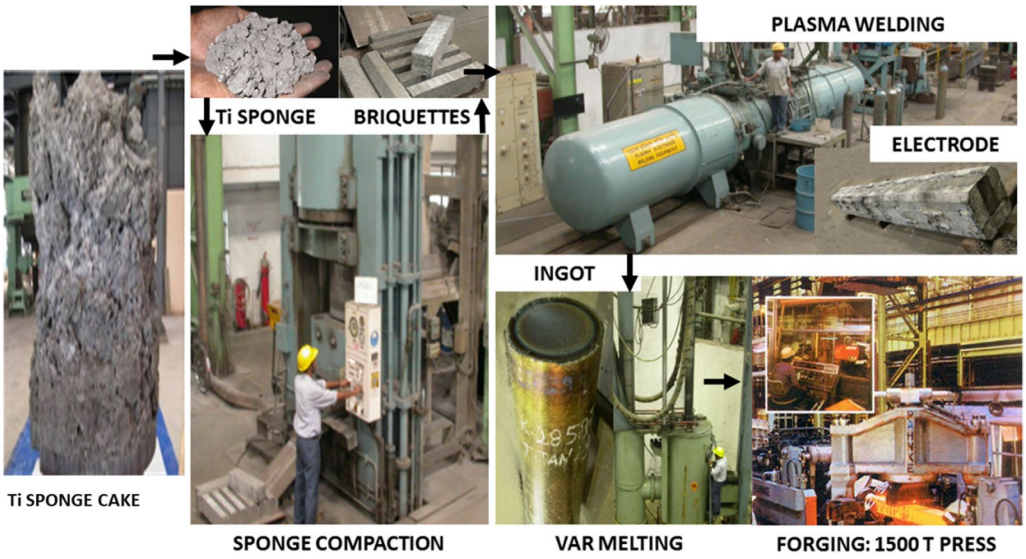

Figure 9: Process flow for production of titanium alloy mill products. Note: arrow marks show the sequence of processing steps- Alloying addition and compaction of Titanium sponge to get compacted briquettes, plasma welding of briquettes of form the electrode, melting of electrode using VAR melting furnace to obtain Titanium alloy ingots and forging operation in a hydraulic press[36].

catastrophically failed during proof pressure testing at cryogenic temperature (77 K) is presented in Fig. 11. The optical microstructures, inverse pole figures and the fractographs of the failed domes reveal significant differences among the two welded domes. While one dome has an equiaxed grain structure that resulted in a ductile fracture, the other half of the electron beam welded dome has lamellar microstructure with microcracks that results in brittle cleavage failure. The failure was attributed to higher than permissible hydrogen content present in the material that was picked up during the thermo-mechanical processing stage, for a product to be used at the lower operating temperatures. A vacuum annealing step was introduced subsequently to limit the hydrogen content which proved to be successful. Figure 12 shows the processing sequence of metallic thermal protection system using Titanium aluminide. indicating the sequence of various processing steps involved.

Electron beam welding technology for joining the hemi-spherical domes was established for different materials used for gas bottles (CP-Ti, Ti-6Al-4V, both ELI and non-ELI grades and Ti-5Al-2.5Sn) and these bottles are now routinely used in PSLV and GSLV/GSLV MkIII flights. The production of these hemispherical dome forgings is carried out at M/s SIFL, Thrissur and M/s Bharat Forge, Pune, and their welding is carried out at M/s Brahmos Aerospace, Trivandrum.

One of the performance-critical applications of titanium alloy Ti-6Al-4V is in the large sized propellant tanks for upper stages of launch vehicles and satellites. These are fabricated from large sized rings/shells and domes and are joined by electron beam welding. Satellite propellant tanks are fabricated to stringent quality control specifications as they serve up to 15 years in orbit. The rings required for the propellant tanks are processed at M/s MIDHANI, Hyderabad and M/s Bharat Forge, Pune and are welded at Electron Beam Welding facility at LPSC, Bangalore. These propellant tanks are being routinely produced and flown for different satellite missions.

It is matter on great satisfaction that ISRO in association with DMRL, Hyderabad has established a state-of-the art Titanium sponge plant at KMML, Chavara, in Kerala to produce 500 TPA titanium sponge using technology developed by DMRL. The sponge produced is used for melting titanium alloys of various grades at M/s MIDHANI. With the establishment of this plant, India joined the select club of countries having end-to-end capability of producing titanium- from 'Sand to Space'.

Table 5: Chemical composition, applicable international standards and T_β of a few Ti alloys used for space applications[36].

Alloy	Applicable Standards	T_β, K	Al	Mo	V	Fe	Cr	Si	Zr	C	Sn	O	N	H	Ti
			Wt.% (nominal)				Wt. % (max.)								
Near-α-Ti alloys															
CP-Ti(Gr2)	AMS 4902	1163–1193	–	–	–	–	–	–	–	0.10	–	0.25	0.03	0.015	99.6
CP-Ti(Gr4)	AMS 4901	1173–1203	–	–	–	–	–	–	–	0.10	–	0.40	0.05	0.015	99.4
Ti-5Al-2.5Sn-ELI	AMS 4909, AMS 4924	1263–1293	5.0	–	–	0.30	–	0.15	0.30	0.05	3.0	0.12	0.05	0.015	Rem.
(α + β)-Ti alloys															
Ti-6Al-4V	AMS 4928, AMS 4911	1253–1283	6.0	–	4.0	0.30	–	0.15	–	0.08	–	0.2	0.05	0.015	Rem.
Ti-6Al-4V-ELI	AMS 4930, AMS 4931	1233–1263	6.0	–	4.0	0.30	–	0.15	–	0.10	–	0.13	0.03	0.015	Rem.
Ti-3Al-2.5V	AMS 6940, AMS 4943	1273–1293	3.0	–	2.5	0.25	–	–	–	0.05	–	0.12	0.02	0.015	Rem.
BT-14	GOST 19807	1213–1233	4.5	3.0	1.0	0.30		0.15	0.30	0.10	–	0.15	0.05	0.015	Rem.
BT-23	GOST 19807	1258–1288	5.5	2.0	4.5	0.6	1.1	0.15	0.30	0.10	–	0.15	0.05	0.015	Rem.
Metastable β-Ti alloys															
Ti-15V-3Cr-3Sn-3Al	AMS 4914	1023–1043	3.0	–	–	3.0	15.0	–	–	0.05	3.0	0.13	0.05	0.015	Rem.
BT-22	GOST 19807	1093–1153	5.0	5.0	5.0	1.0	1.0	0.15	–	0.10	–	0.20	0.05	0.015	Rem.
Ti-10V-2Fe-3Al	AMS 4983	1063–1078	3.0	–	10.0	2.0	–	–	–	0.05	–	0.13	0.05	0.015	Rem.

Table 6: Ti alloys for space applications: deformation mode, HT condition, HT cycle and mechanical properties[36].

Sl. no.	Alloy	Components/applications	Manufacturing route/deformation temperature	HT condition	HT Cycle	Mechanical properties (min.)			
						0.2%P.S, MPa	UTS, MPa	%El (4d)	K_{IC}, MPa. $m^{1/2}$
1.	CP-Ti (Gr.2/Gr.4)	Propellant tanks for satellites	Closed die forging- Hammer: T: 1123–1013 K	Annealed	923 K-1 h-A/c	275 483	345 550	20 15	–
2.	Ti-5Al-2.5Sn-ELI	Cryogenic gas bottles- liquid H_2 environment, LH_2 impeller, brackets for 20–77 K applications	Closed die forging-Hammer: Temperature- 1283–1173 K	Annealed	953–1063 K-1 h-A/c	689	758	8	–
3.	Ti-3Al-2.5	Tubes for structural applications	Pilgering/ cold drawing	Annealed	923–1063 K-1 h-A/c	517	620	15	–
4.	Ti-6Al-4V	High pressure helium gas bottles and COPV liners, rings and domes for propellant tanks for ambient temperature applications	Closed die forging- Hammer:	Annealed	973 K -1 h-A/c	825	895	10	50
			T: 1223–1113 K	STA	1228 K- 1 h-WQ + 783 K-4 h-A/c	960	1030	10	38
5.	Ti-6Al-4V-ELI	High pressure helium gas bottles for liquid oxygen environment, > 77 K applications	Closed die forging- Hammer: T: 1223–1113 K	Annealed	973 K-1 h-A/c	768	827	10	60
6.	BT-14	Launch vehicle stage separation system components for applications ~ 90 K	Closed die forging: 1173–1103 K	Annealed	1123 K-1 h-A/c	840	890	10	–
7.	Ti-15V-3Cr-3Sn-3Al	Candidate material for skin panels for reentry launch vehicle and high pressure gas bottles	Hot rolling: T: 1198–1063 K and cold rolling	STA	1003 K-1 h-A/c + 793 K-8 h-A/c	1150	1300	8	–
8.	BT-22	Candidate material for landing gear for reentry launch vehicles and high pressure gas bottles	Forging: T: 1103–1023 K	STA	1093 K-1 h-A/c + 793 K-6 -A/c	1060	1150	8	–

Figure 10: Various titanium alloy mill products in different grades and fabricated components used for space applications[36].

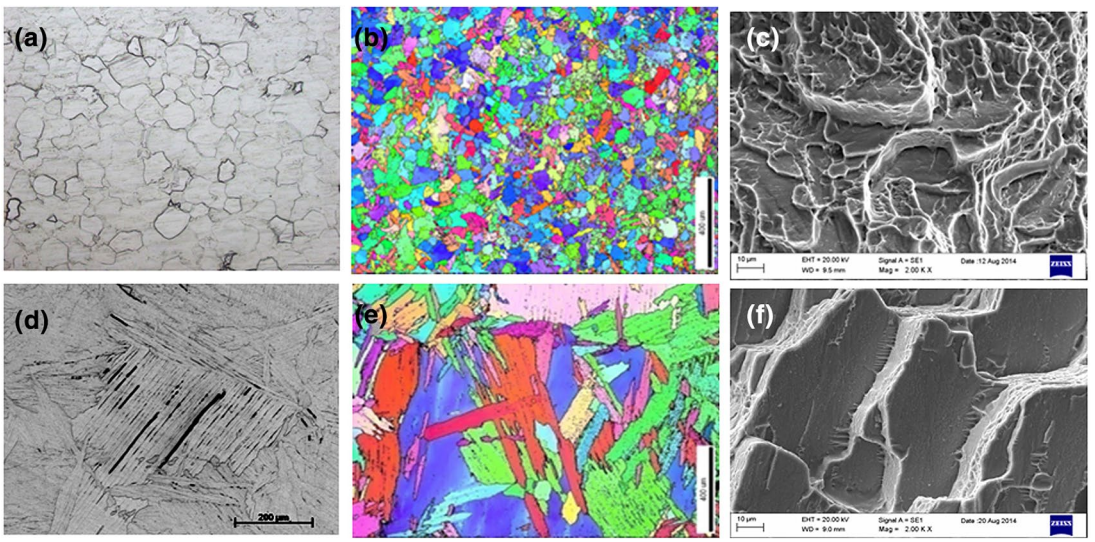

Figure 11: Details of catastrophically failed Ti-5Al-2.5Sn gas bottle with separation of top and bottom domes in to near equal halves. The optical microstructures (**a**, **d**), inverse pole figures (**b**, **e**) and the fractographs (**c**, **f**) of the failed domes reveal significant differences among the two welded domes. While one dome has an equiaxed grain structure that resulted in a ductile fracture, the other half of the electron beam welded dome has lamellar microstructure with micro-cracks that resulted in brittle cleavage failure.

6 Special Steels for Cryogenic Engines

Cryogenic rocket engines of space launch vehicles use liquid hydrogen (boiling point = 20 K) and liquid oxygen (boiling point = 90 K) as fuel and oxidizer respectively. During the operation of these engines, many of the parts of engine are exposed to these extreme temperatures[45]. One of the important characteristics of materials selected for these applications is the retention of mechanical properties, especially ductility and toughness at the low temperatures. The material should also be amenable to fabrication into different shapes and hence formability and weldability are the primary material selection criteria. In an actual engine, these steels are subjected to different welding/brazing operations and heat treatment conditions

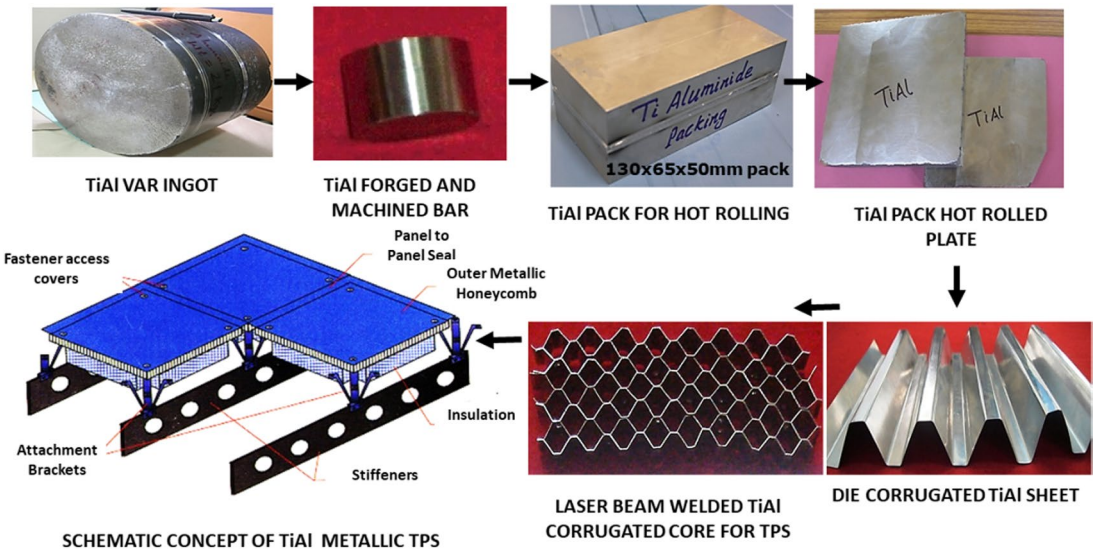

Figure 12: Processing sequence of metallic thermal protection system using TiAl. Note: arrows indicate the sequence of various processing steps involved[36].

Figure 13: Typical components fabricated from stainless steels for launch vehicle applications.

which changing their microstructural condition. It is very important that the material in the final fabricated condition should meet the low temperature mechanical properties, especially toughness which ensures that the material has not been embrittled during processing operations. Austenitic stainless steels, due to the absence of DBT, excellent combination of mechanical and physical properties and adequate fabricability have long been used for a wide array of low temperature applications.

For cryogenic applications, the existing austenitic stainless steels have been improved by reducing the impurity levels through premium vacuum melting processes. In contrast to lean austenitic steels like AISI 304 and AISI 304L, austenitic grade AISI 316L shows improved structural stability. No spontaneous martensitic transformation due to quenching is observed in this grade. However, martensitic transformation through deformation persists. This grade is usually preferred for pre-formed thin-walled structures. AISI 301 stainless steel can be hardened to tensile strengths of over 2000 MPa owing to favorable transformation of unstable austenite into martensite. The leaner austenitic steel grades are usually cold worked for improved strength while retaining ductility. AISI 202 austenitic stainless steel exhibits excellent cryogenic properties, for its impressive combination of toughness and corrosion resistance and is used in impeller applications in cryogenic engines operated at 20 K. Figure 13 shows some of the typical components fabricated from stainless steels for low temperature applications.

It must be noted that the low yield strength of austenitic stainless steels poses a major problem for weight critical cryogenic applications, especially for high thrust rocket engines. This limitation has led to the development of a group of precipitation hardened (PH) stainless steels for aerospace applications. The development of martensitic PH stainless steels, with a BCC matrix required optimization at several fronts such as control of interstitials by premium melting practices and alloy design that provides optimum strengthening without loss of cryogenic toughness. The PH stainless steels used for applications at cryogenic temperatures in cryogenic and semi cryogenic rocket engines and associated systems include 14-5PH, A286, 11Cr-9Ni and 12Cr-10Ni grades [46–49]. All these steels have been indigenously produced meeting the specified requirements. Figure 14 shows the variation of fracture toughness versus YS at 77 K and 4 K for different types of steels used for cryogenic applications.

7 Superalloys for Hot Structures

Superalloys are materials of choice for several high temperature applications in aerospace engineering due to their ability to retain strength at elevated temperatures[50–53]. Amongst superalloys, nickel based super alloys are preferred because of the combination of their high strength and oxidation resistance. Composition-microstructure-mechanical properties correlation in nickel-based superalloys is dependent on the physical metallurgy of the superalloys. Optimization of processing parameters during the hot working of superalloys to obtain the desired microstructure is one of the most important aspects during thermo-mechanical processing.

One of the most widely used material among the nickel based superalloy is Inconel alloy IN718. Inconel alloy IN718 and its equivalent alloys are used in High thrust Vikas engine gas generator, C20 turbine rotor, as duct material in cryogenic engine, as turbine disc in semi-cryo engine and as struts in air breathing engine in ISRO launch vehicles. IN718 is also material of choice for the high pressure oxygen gas bottles for environmental control and life support system of human spaceflight project[54,55]. It was also used as a casing material for Nickel-Hydrogen cell cases and the technology for deep drawing of such shells was established in ISRO[56–58]. Additive manufacturing of some of these parts out of IN718 has distinct advantages in terms of shorter lead times. However, it is essential to study the effect of microstructure on the room and high temperature mechanical properties to understand their behavior under operating conditions. Further, study of the role of printing defects on mechanical properties and behavior of parts under operating conditions is essential and the role of hot isostatic pressing on the healing of defects for performance critical applications such as rotating parts, parts operating at extreme temperatures should be studied.

One of the superalloys that is used for the nozzle divergent of liquid engine is a Cobalt based superalloy (Co-20Cr-15W-10Ni) commercially known as KC20WN[59,60].This material has a 0.2% yield strength of 340–540 MPa, ultimate tensile strength of 880–1080 MPa and an elongation of 30%. It should meet the stress rupture test with an elongation of 8% with more than 15 h life at 950 °C at a stress of 8 kg/mm^2. A thermal barrier coating of calcia stabilized zirconia coating is given on the inner portion of the divergent. Obtaining the desired properties at the final sheet level demands careful processing of the material with controlled chemistry and thermo-mechanical processing steps. Figure 15 shows the montage of optical photo micrographs of cobalt based superalloy KC20WN obtained from isothermal hot compression tests conducted at varying temperatures and strain rates.

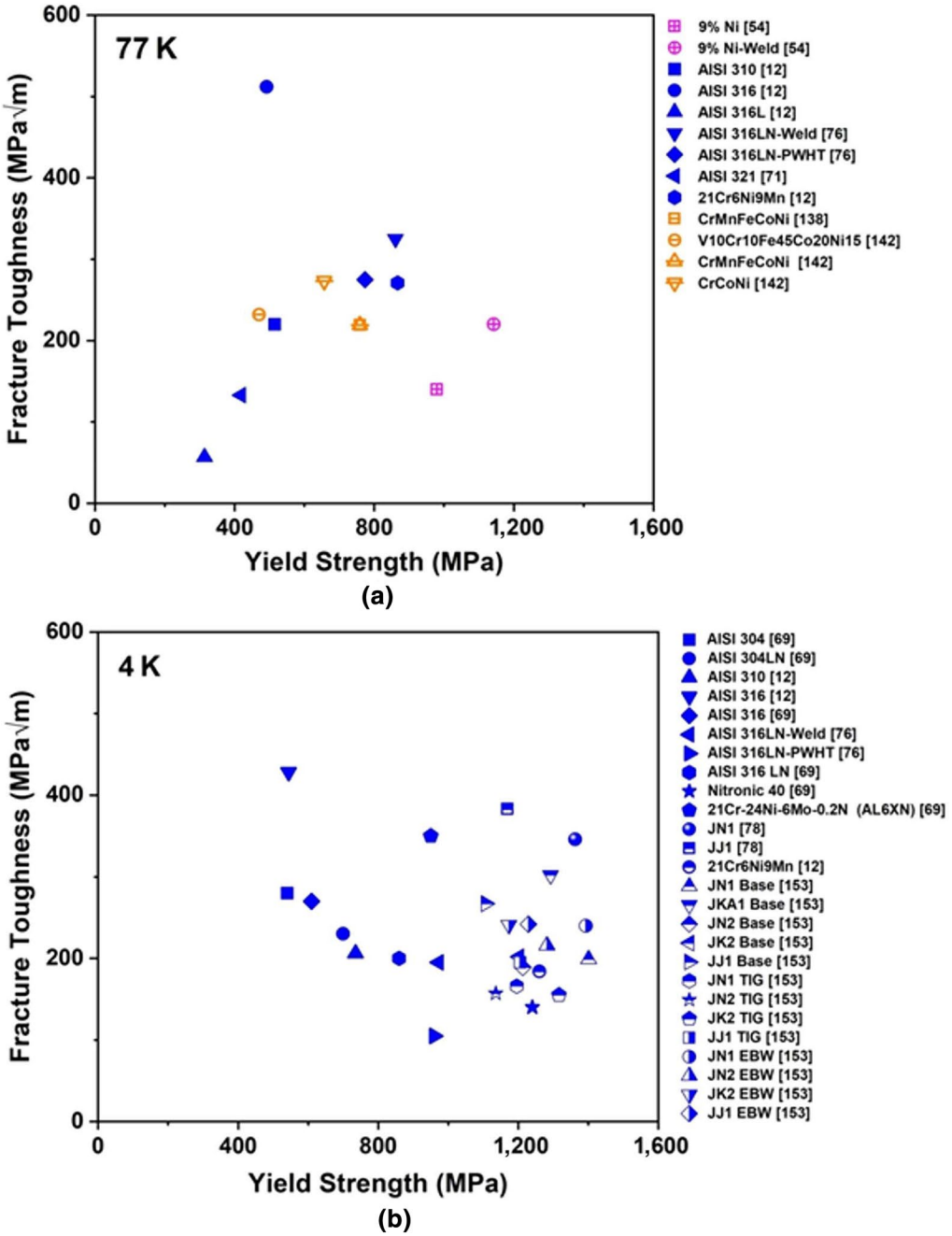

Figure 14: **a** Fracture toughness versus YS at 77 K. **b** Fracture toughness versus YS at 4 K for different types of steels used for cryogenic applications.

8 Copper Alloys for Thrust Chambers

Copper is a natural choice for engineering applications requiring rapid heat transfer. It is used from common industrial applications to sophisticated engineering applications such as nuclear reactors and rockets. Even though pure copper has very high thermal conductivity (399 W/m.K), it has unacceptably low mechanical properties for any meaningful structural applications. Therefore, Cu is usually alloyed with Cr, Nb, Ag, Zr in different combinations to improve its mechanical strength. These alloys provide a good combination of mechanical strength and thermal/electrical conductivity for elevated temperature applications. Therefore, Cu-based alloys and composites find applications in the first wall-and-diverter components in fission, magnetic confinement fusion reactors, combustion chamber liners

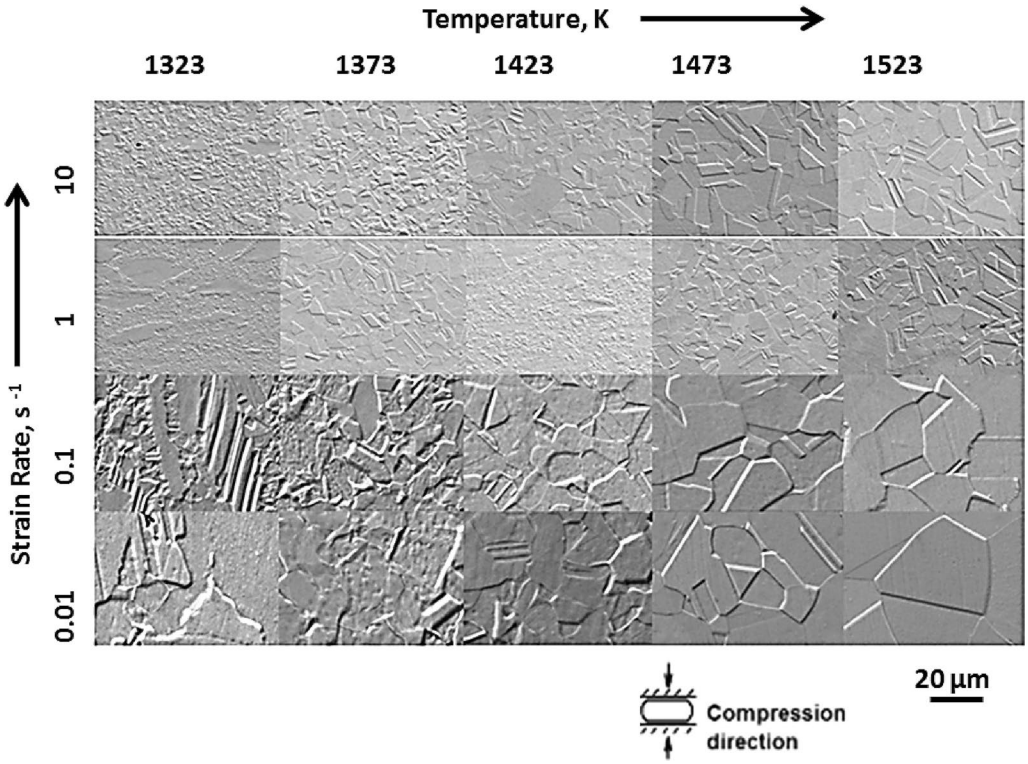

Figure 15: Montage of optical photo micrographs of cobalt based superalloy KC20WN used in the rocket nozzle divergent applications. The optical microstructures are obtained from isothermal hot compression tests conducted at widely varying temperatures and strain rates with an intention to optimize the hot workability and control the grain structure during the hot deformation processing of the material [59].

for Reusable Launch Vehicle (RLV) engines and rocket nozzle liners which demand active-cooling applications. To meet critical design requirement, continuous efforts are under way to develop Cu-based alloys and composites with improved high temperature properties. However, use of alloying additions or second phase such as precipitates or dispersoids to enhance the mechanical properties invariably leads to decrease in thermal conductivity of the material, which annuls the basic material selection criteria (i.e. thermal conductivity) fulfilled by Cu for such applications. Therefore, the fundamental criterion for such applications is the design of copper alloy by enhancing high temperature strength without compromising thermal conductivity.

Cu-0.7Cr-0.05Ti-0.05Zr alloy is used for the inner liners of nozzle divergent section in cryogenic and semi-cryogenic engines of Indian launch vehicles[61–64]. This alloy has been successfully indigenized and flown in space missions. Extensive developmental work on ingot metallurgical processing, thermomechanical processing, multi-stage deep drawing and vacuum brazing with outer steel shell were carried out and the end-to-end process has been established. Many technical challenges were overcome as a part of the developmental work. Figure 16 presents an such example of cracking of thrust chamber throat after testing[64]. The figure shows digital photographs of the convergent-divergent section of the thrust chamber. The photograph of a portion with crack of about 78 mm length and close-up view showing different regions at and away from the cracked location are also presented. The cracking was attributed to the thermal ratchetting leading to the failure of the throat region. Optical photomicrographs showing the location of the dog-house effect and associated grain coarsening as well as location away from the dog-house region showing uniformly fine grains are also presented. Dog-house effect is a structural failure mode of regeneratively cooled rocket combustion chambers which is caused by cyclic, thermo-mechanical loading. In this phenomenon, the hot-gas side wall becomes thinner and bulges towards the interior of the combustion chamber.

The GRCop-84 (Cu-8at%Cr-4at%Nb) is a dispersion hardened alloy having hard and stable intermetallic Cr2Nb precipitates. The alloy is commonly processed by powder metallurgical techniques. GRCop-84 alloy has revealed

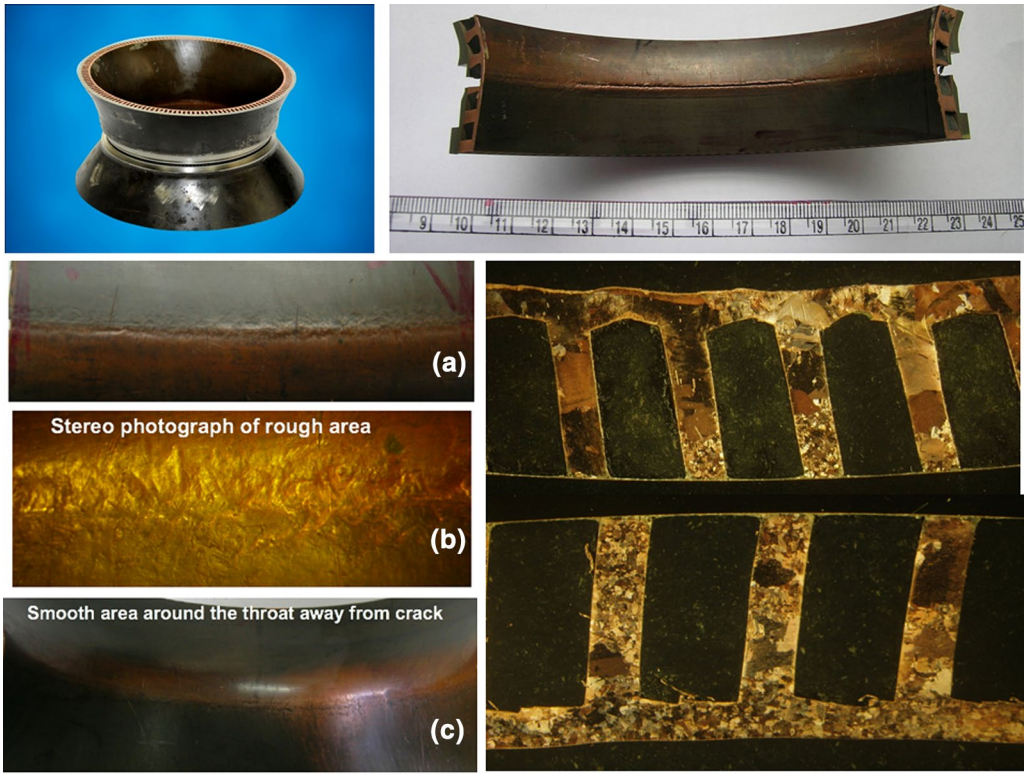

Figure 16: (Top left) Photographs of the convergent-divergent section of the thrust chamber global view with the top being the convergent section; the middle being the throat region, and the bottom being the divergent section of the thrust chamber; (top right) photograph of a portion with crack of about 78 mm length; (bottom left) close-up view photograph showing different regions at and away from the cracked location; (bottom right) optical photomicrographs showing the location of the dog house effect and associated grain coarsening as well as location away from the dog house region showing uniformly fine grains[64].

the best combination of properties required for rocket engine applications compared to other candidate Cu-based materials. ISRO has developed the powder metallurgical processing of GRCOP-84 to obtain vacuum hot pressed products that can be further processed to different shapes[65–70].

9 Magnesium Alloys for Upper Stages and Inertial Systems

Being the lightest structural alloy coupled with very high specific strength, damping capacity and dimensional stability, magnesium alloys find extensive applications as secondary structures of launch vehicles and satellites in Indian space programs. In view of its attractive properties, it is used in multiple applications. Magnesium alloy AZ92 was used for A 3-axis rate gyro mounting block of SLV-3. ASLV used magnesium alloy components for inertial platform module of the Stabilized Platform Inertial Navigation System (SPINS). Magnesium alloy complex castings were developed for PSLV for cluster and housings for the Redundant Strap-down Inertial Navigation Systems (RESINS). Other significant developments in magnesium alloys include Payload adapter in ZK30 ring rolled rings. Today, India has self-sufficiency in all magnesium alloy products required for launch vehicle and satellite applications.

Due to their high chemical reactivity and poor workability, processing of these alloys is formidable in nature [[71]]. ISRO has successfully developed casting technology of AZ92 and ZE41 alloy components, forging and rolling parameters of AZ 31 alloys, ring rolling and extrusion technology of ZK30 alloy, processing technology of ultralight Mg-Li alloys and welding technologies of ZM21, AZ31 and LA141alloys. Figure 17 presents various types of magnesium alloy products used in the launch vehicle program. The typical view of an equipment bay at the centre and various types of magnesium castings used for mounting

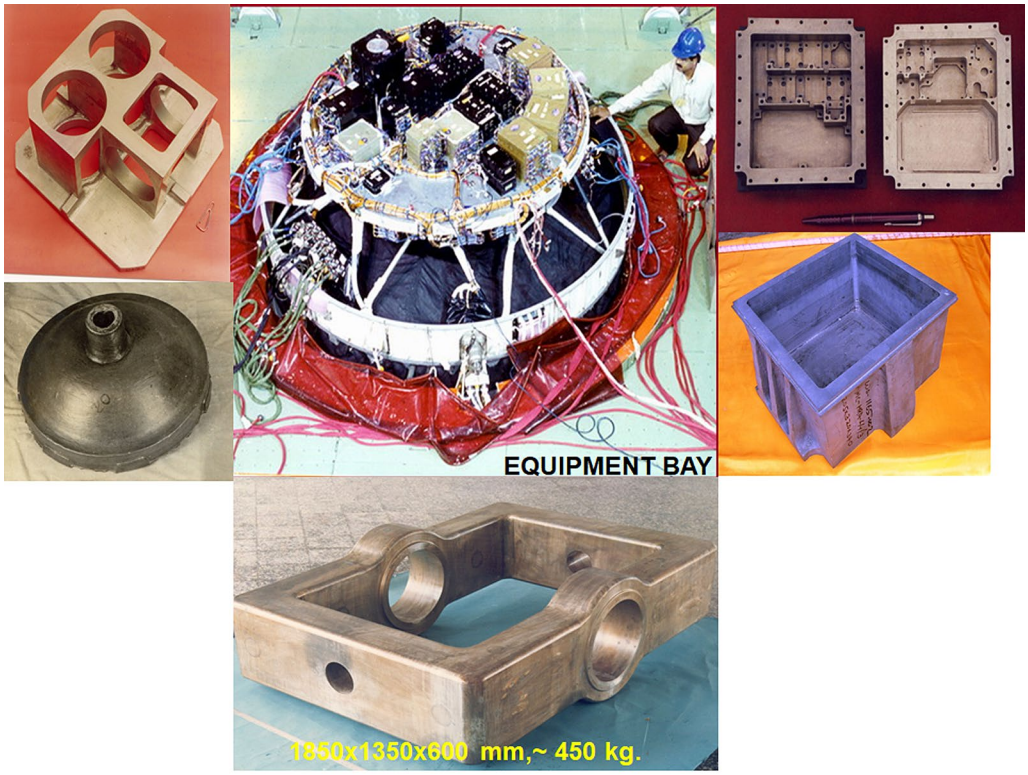

Figure 17: Typical view of an equipment bay (center) and various types of magnesium castings used for mounting the electronic packages. Bottom photograph shows a large magnesium casting for angular motion simulator.

the electronic packages is presented. A significant achievement has been the development of 'Outer Axis Gimbal for Angular Motion Simulator' in association with Indian industry. This is the largest (1850 × 1350 × 400 mm size) and heaviest (rough casting weight > 400 kg) magnesium alloy casting in the country so far.

10 Refractory Materials: Indigenous Production of Niobium and Hafnium Metals

Refractory materials are extensively used in launch vehicle thrust chambers, radiation skirts for rocket and aircraft engines, rocket nozzles, thermal shields, leading edges and nose caps for hypersonic flights[72,73]. Even though refractory metals are characterized by high melting points, they readily get oxidized at moderate temperatures, which restricts their processing and applications. Niobium alloy with composition Nb–10Hf–1Ti (C-103) was developed and used due to its excellent fabricability and weldability. Addition of Ti ensures microstructure stability at high temperature, and Hf controls grain size. Further, titanium and Hf increase the oxidation resistance by the formation of external tough oxide layer and decreasing the diffusivity of oxygen, respectively. Among the niobium alloys for high temperature applications, C103 can be used up to 1400 °C as it retains tensile strength of 90 MPa at 1370 °C. C103 is the material of choice in space industry for divergent sections of liquid apogee motors and as thrusters in attitude orbital control systems. These components are given silicide coatings for oxidation resistance.

ISRO has established facility for the extraction of Niobium metal from the Niobite-Pyrochlore ores in association with Nuclear Fuel Complex, Hyderabad. Indian Columbite-Tantalite ore occurs in mica belt of India. The mineral resources Niobite- tantalite $(Fe,Mn)(Nb,Ta)_2O_6$ and Pyrochlore ($NaCaNb_2O_6F$) after crushing, pulverizing and ore dissolution are subjected to solvent extraction, calcination and aluminothermic reduction to obtain Niobium metal. The chemical composition of the Niobium obtained corresponds to Niobium > 99.5; Nitrogen < 0.03; Oxygen < 0.2; Hydrogen < 0.01; Carbon < 0.03; Silicon < 0.005; Nickel < 0.005; Tantalum < 0.100; Iron < 0.005; Hafnium < 0.005; Titanium < 0.005;

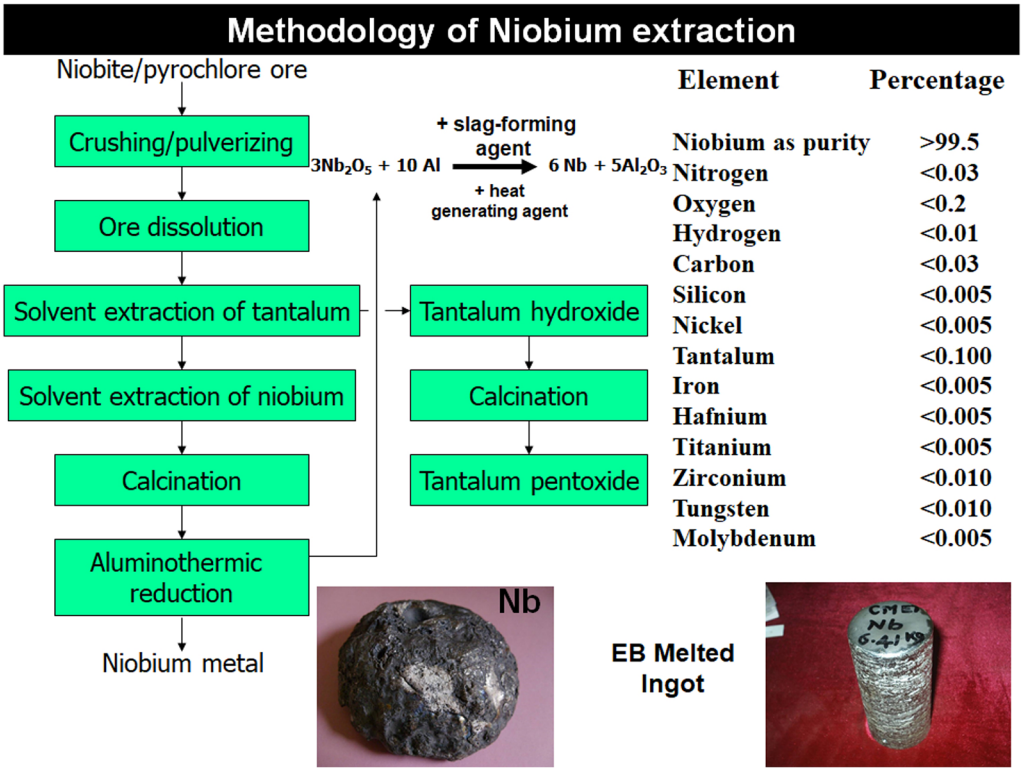

Figure 18: Flow sheet for extraction of niobium metal along with the photographs of niobium metal as well as the achieved chemical composition.

Zirconium < 0.010; Tungsten < 0.010; Molybdenum < 0.005. Figure 18 shows the flow sheet for extraction of niobium metal along with the photographs of Niobium metal as well as the achieved chemical composition.

Hafnium is an important metal, both for nuclear and space sectors. As pure metal, Hf is used in control rods for nuclear applications, as alloying element in Nb based alloys (C-103) for space applications as well as in superalloys. In its compound form, it is used as HfB2 based Ultra High Temperature Ceramics (UHTC) for Space Re-entry Vehicles apart from HfO2 for microprocessors and HfC for high temperature applications. Hafnium chemically resembles zirconium and is found in zirconium minerals. It is estimated to make up about 5.8 ppm of the Earth's upper crust by mass. It does not exist as a free element in nature, but present as solid solution with zirconium in natural zirconium compounds such as ZrSi04.

In view of its strategic nature and in order to achieve self-sufficiency, ISRO has taken the lead to establish hafnium metal production facility in India. Establishment of a plant to produce 320 kg/ annum of hafnium sponge at M/s. C-MET, Hyderabad with indigenous technology is one of the critical milestones of ISRO to achieve self-reliance in the production of this strategic metal. Presently hafnium metal is imported and establishment of this plant at C-MET, Hyderabad eliminated the dependency on foreign sources for this strategic metal. Figure 19 shows the flow sheet for extraction of Hafnium metal from zirconium scrub raffinate. Through a series of complex processes involving solvent extraction, calcination, carbochlorination, Hafnium tetra chloride is produced which is reduced using Kroll's process) to Hafnium metal. The first indigenous pilot plant was established to produce space grade hafnium metal and all the process equipment's for this plant were designed and fabricated indigenously which is fully operational. Hafnium with purity > 99% was obtained by this process and the chemical composition of the metal is Iron < 0.03; Zirconium < 0.5; Chromium < 0.01; Carbon < 0.01; Aluminium < 0.005; Nickel < 0.005; Oxygen < 0.3 (all in weight percentage) with balance Hf. Qualification of the process is carried out at various stages right from raw material preparation to the final vacuum distillation process and it is found that the hafnium

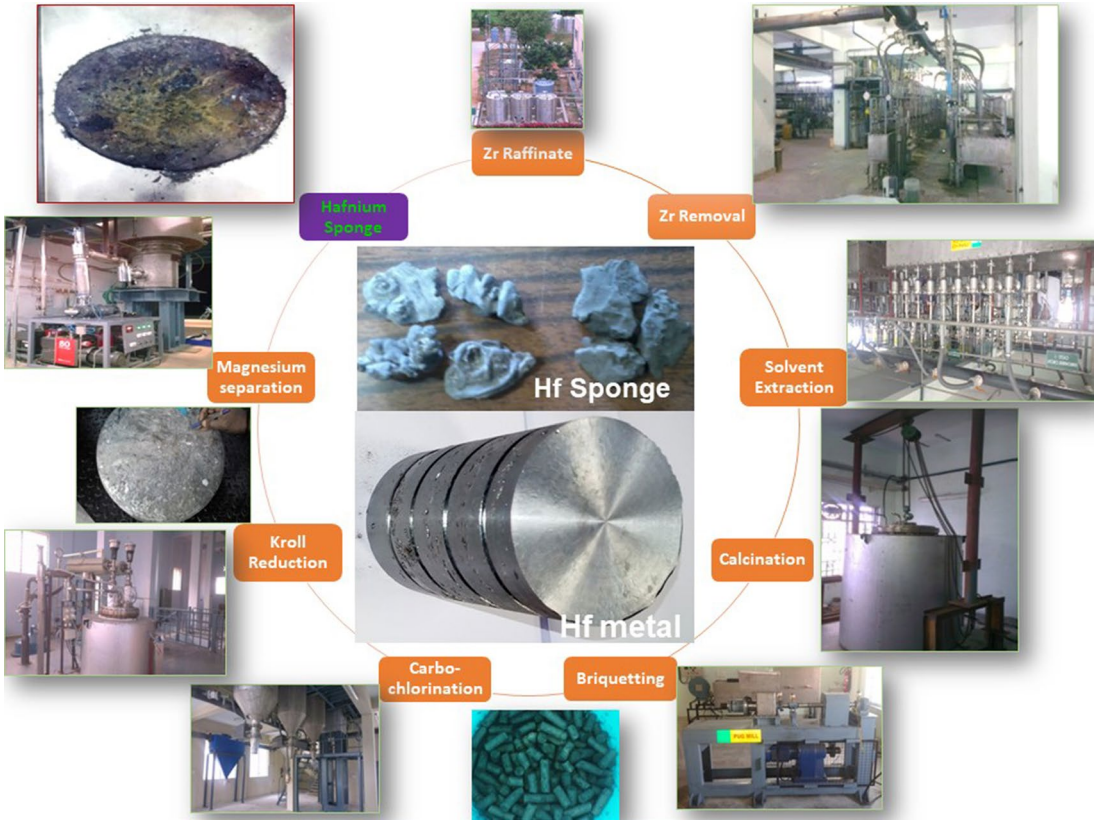

Figure 19: Flow sheet for extraction of Hafnium metal along with the achieved chemical composition.

sponge produced during the qualification trials are meeting the specifications requirements for the hafnium sponge laid by ISRO for further refining processing of C-103 alloy.

11 Investment Castings for Cryogenic and Semi-Cryogenic Engines

Some of the parts of rocket engine that have intricate shapes, internal cavities, complex vanes of impellers where the propellants flow through such as turbopumps are made by investment casting process. Investment casting or lost-wax process uses a ceramic shell mould. Wax patterns dipped in ceramic slurry are fired to obtain a shell to pour liquid metal. Intricate shaped precision castings with good internal finish can be obtained through this process. Large number of investment castings are used in cryogenic and semi-cryogenic engines of launch vehicles.

The GSLV uses fourteen types and GSLV-mkIII uses four types of investment castings, both of which have been successfully flown. Semi-cryogenic engine is being developed to meet the future launch vehicle requirements which works on oxidizer rich staged combustion cycle and delivers a vacuum thrust of 2000 kN. The propellants are liquid oxygen (LOX) and Isrosene. This engine is to operate for a nominal duration of around 355 s. As many as 18 types of investment castings are required for the realization of this engine including 11 types for realization of turbopump subsystems and 7 types for control components. All these intricate castings are realized through investment casting route to achieve close dimensional tolerance and very good surface finish. These castings are mainly made up of stainless steels and superalloys. Figure 20 shows typical investment cast products used in the cryogenic and semi-cryogenic engines of launch vehicles.

There are many challenges in the development of these investment castings including design of the gating systems, prediction of the location of possible defect formation, meeting the quality control requirements with respect to non-destructive test procedures, optimization of heat treatment schedules, repair welding of defective castings and hot isostatic pressing for defect healing and establishment of detailed

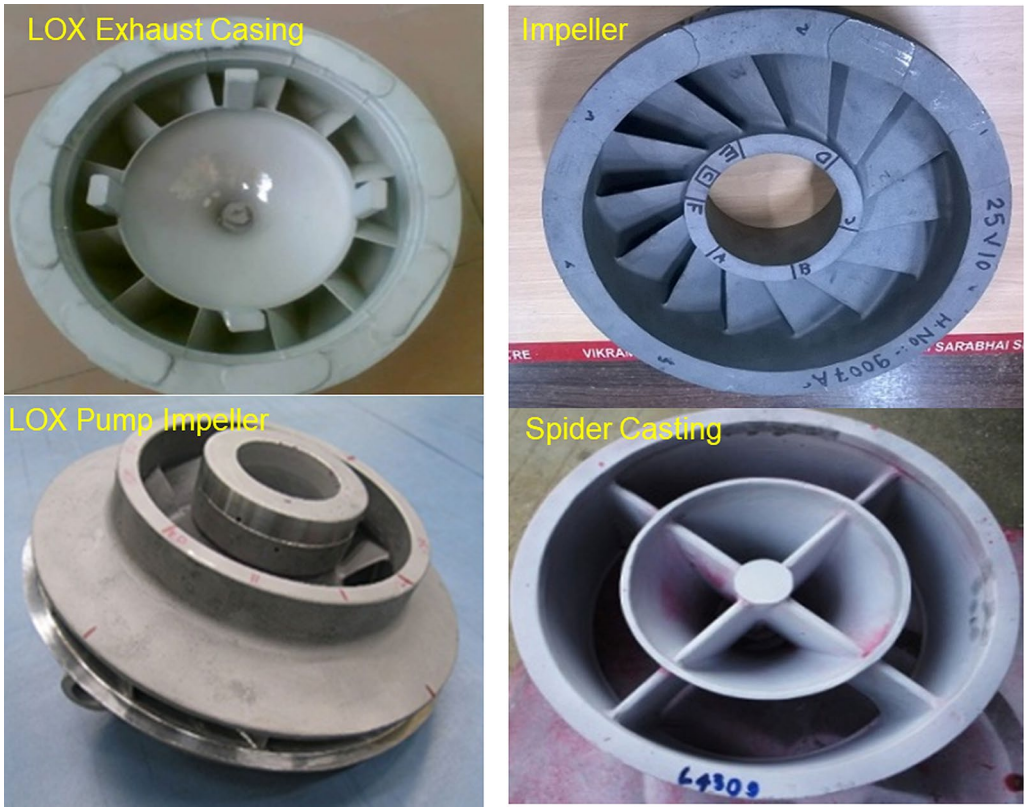

Figure 20: Different types of investment cast products used in launch vehicles.

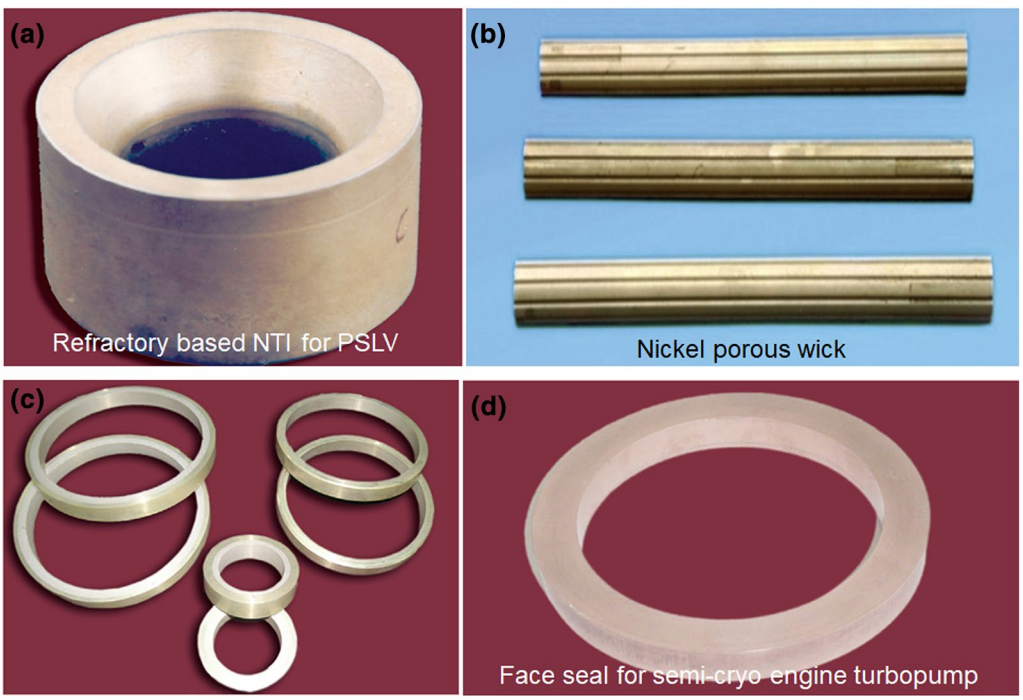

Figure 21: Powder metallurgically processed components for launch vehicle and satellite applications.

procedures. Extensive modeling and simulation studies using commercial software like Procast™ are routinely used for design of the gating design[74–76]. Several Indian industries are participating in the manufacture of these castings. These investment castings have been successfully flown in GSLV and GSLV mkIII vehicles.

12 Special Purpose Materials

12.1 Powder Metallurgy Materials

For developing small but performance-critical special purpose components for launch vehicle applications, ISRO has adopted PM route[77–81]. Tungsten and Molybdenum based, auto-transpiration cooled, composites have been developed for nozzle throat inserts of bipropellant control thrusters (Fig. 21) involving exposure to high temperatures of the order of 2500^0C and highly oxidizing (54 vol% H_2O) conditions. The inserts have demonstrated excellent dimensional stability along with higher resistance to thermal shock. Brush block technology, based on Ag-graphite and Ag-graphite-MoS_2 compositions developed by ISRO for slip ring assembly of radars, was found to be at par with international standard. Figure 21 shows some of the powder metallurgically processed performance critical components for launch vehicle and satellite applications, including the face seals for turbo-pump systems.

12.2 Magnetic Materials

Soft magnetic alloy ISMCO-45–45, based as Fe-Co-V ternary system shows the highest magnetic induction (B) value of 2.0 T at a small applied field (H) of 10 Oersted. The use of this alloy, as a substitute to the conventional soft magnetic alloys, results in substantial savings in weight, volume and power. Being an intermetallic, it inherits a highly ordered structure with extreme brittleness and therefore, difficult-to-work characteristics. ISRO has successfully established process and characterisation technology of the alloy and its various rod products (Fig. 22) are currently being used as torquer-core onboard INSAT, GSAT and IRS series of satellites.

High energy density rare earth based permanent magnets are indispensable in servo-accelerometers, magnetic bearing reaction momentum wheels, RF switches, gyroscopes, latch valves of AOCS thrusters and special motors required for inertial, navigation, guidance and control systems. In collaboration with DMRL, Hyderabad, ISRO has successfully inducted the indigenously developed $SmCo_5$ magnets for applications in launch vehicles and satellites. Processed by powder metallurgy route, $SmCo_5$ magnets have been realized in different required shapes and sizes. Figure 22 shows soft magnetic alloy ISMCO 49-49 used for torque cores and SmCo5 magnets used for control systems in launch vehicles.

12.3 Bimetallic Materials

Bimetallic components are used where end faces are exposed to different environmental conditions. In the cryogenic engine, there are a large number of such components based on stainless steel-titanium alloy and stainless steel-aluminum alloy. Joining such dissimilar metals is extremely difficult because of difference in density, melting point and other physical and metallurgical characteristics of the materials. ISRO has developed bimetallic joining technology (1) SS 304L to Ti-6Al-4V alloy by diffusion bonding technique and (2) SS ICSS 1218-321 to Al-alloy AA2219 using explosive cladding technique. Figure 23 shows the schematic of explosive bonding process as well as photograph of an explosively bonded bimetallic plate of AISI321 and AA2219 and after machining to different sizes for use in launch vehicles.

12.4 Electronic Ceramics

12.4.1 BMT Ceramics for Satellite Multiplexers

Satellite communication in Ku-band uses a large number of channels handled by devices called multiplexers[82,83]. A satellite may have 60–80 multiplexers leading to a total of about 1000 channels. Such multiplexers have been reduced in size and weight considerably due to special high-permittivity ceramics called dielectric resonators. India has been relying only on imported components till a decade back for these ceramics at a very high cost. ISRO has indigenously produced BMT ceramics (holds a joint patent with CMET-T), qualified and tested space-quality multiplexers for future satellites. ISRO will be able to produce through industries, equivalent quality. Figure 24 shows the photograph of dielectric resonators used in GSAT multiplexers with BMT dielectric resonators assembled in filter cavity along with the comparison of performance characteristics of the indigenously produced and imported dielectric resonators.

12.4.2 DK65 for NAVIC Receiver

Indian Regional Navigation Satellite System, named NAVIC, is for satellite-based navigation around Indian continent. The subscribers need

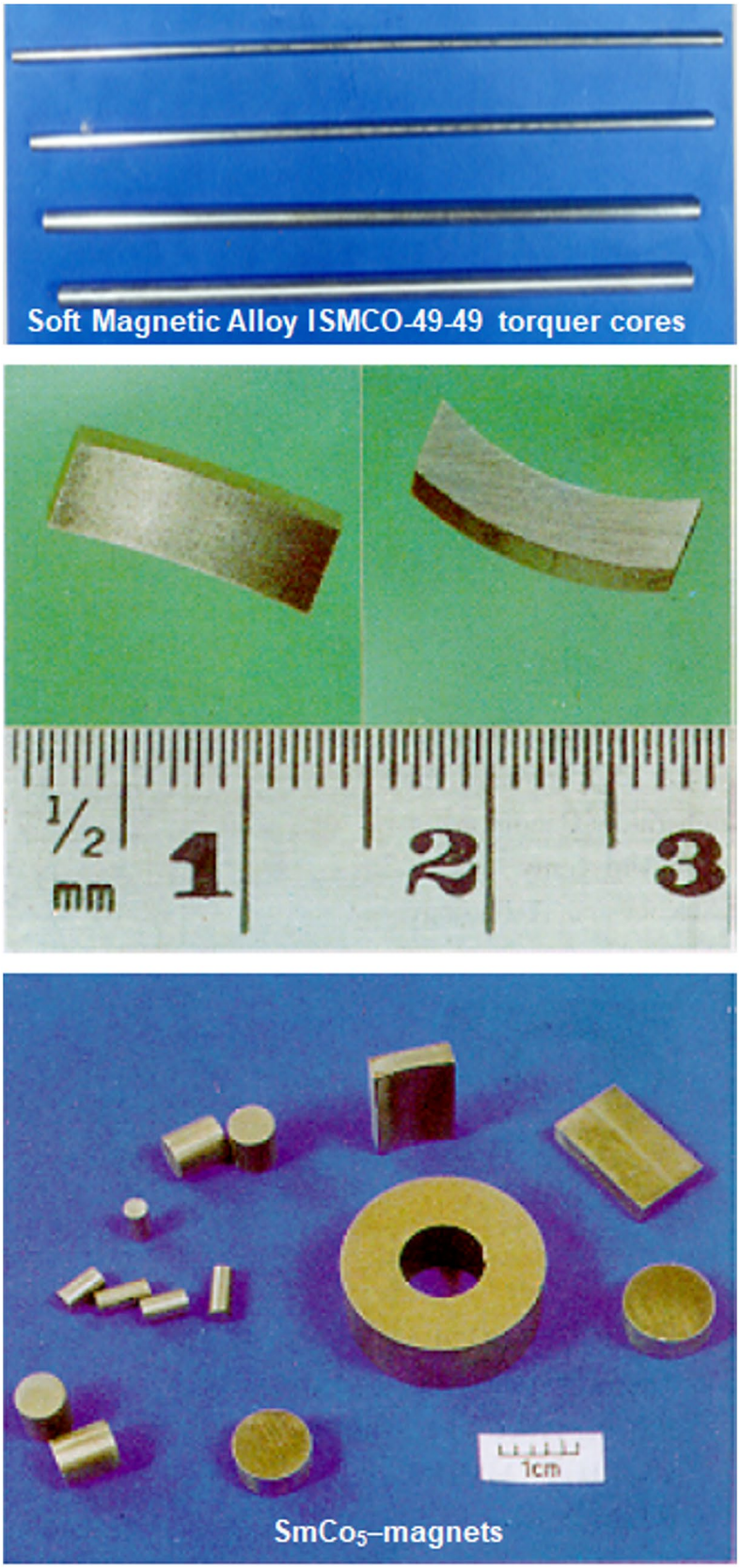

Figure 22: Soft magnetic alloy ISMCO 49-49 used for torque cores and SmCo5 magnets used for control systems in launch vehicles.

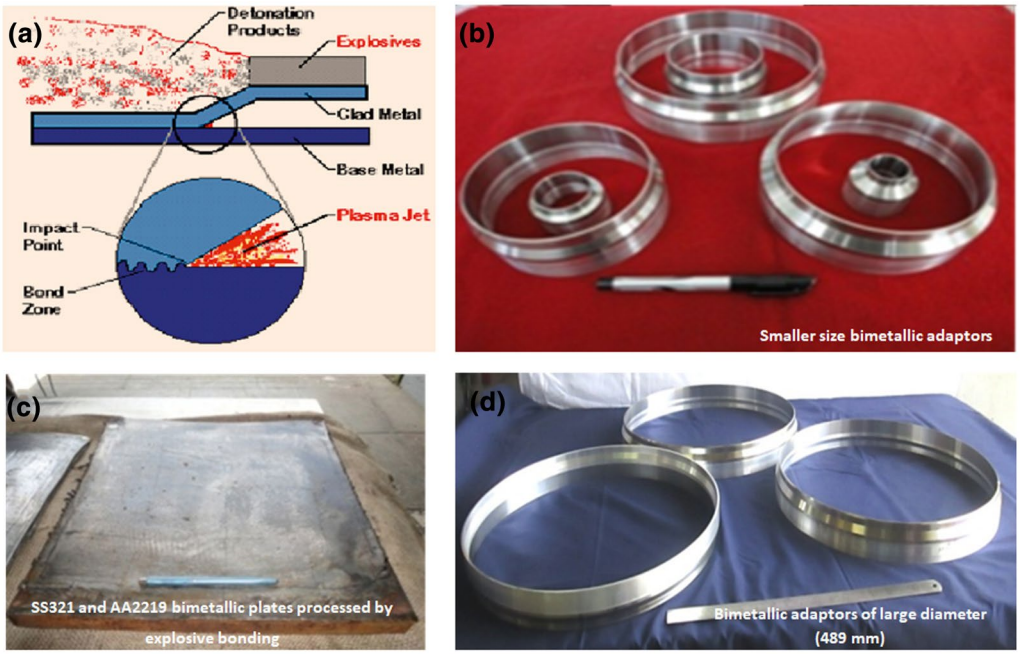

Figure 23: **a** schematic of an explosive bonding process; **c** photograph of an explosively bonded bimetallic plate of AISI321 and AA2219; **b**, **d** machined bimetallic adopters of different sizes used in launch vehicles.

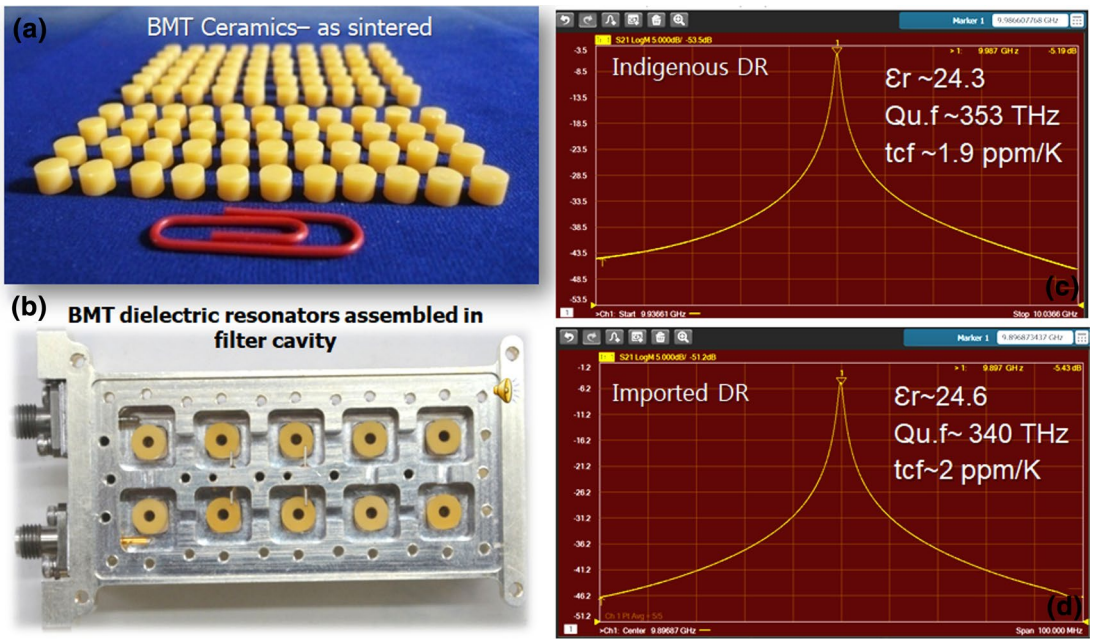

Figure 24: Photograph of dielectric resonators used in GSAT multiplexers **a** BMT dielectric resonators assembled in filter cavity; **b** comparison of performance characteristics of the indigenously produced and imported dielectric resonators (**c**, **d**).

compact receivers, in which, the receiver antenna is the major challenge with respect to miniaturization. Very high-dielectric constant, temperature-stable substrates are required for such an application. ISRO has developed and tested indigenous patch antenna on novel DK65 ceramic substrate, which can be even used for dual band application with small size. Fully indigenous raw

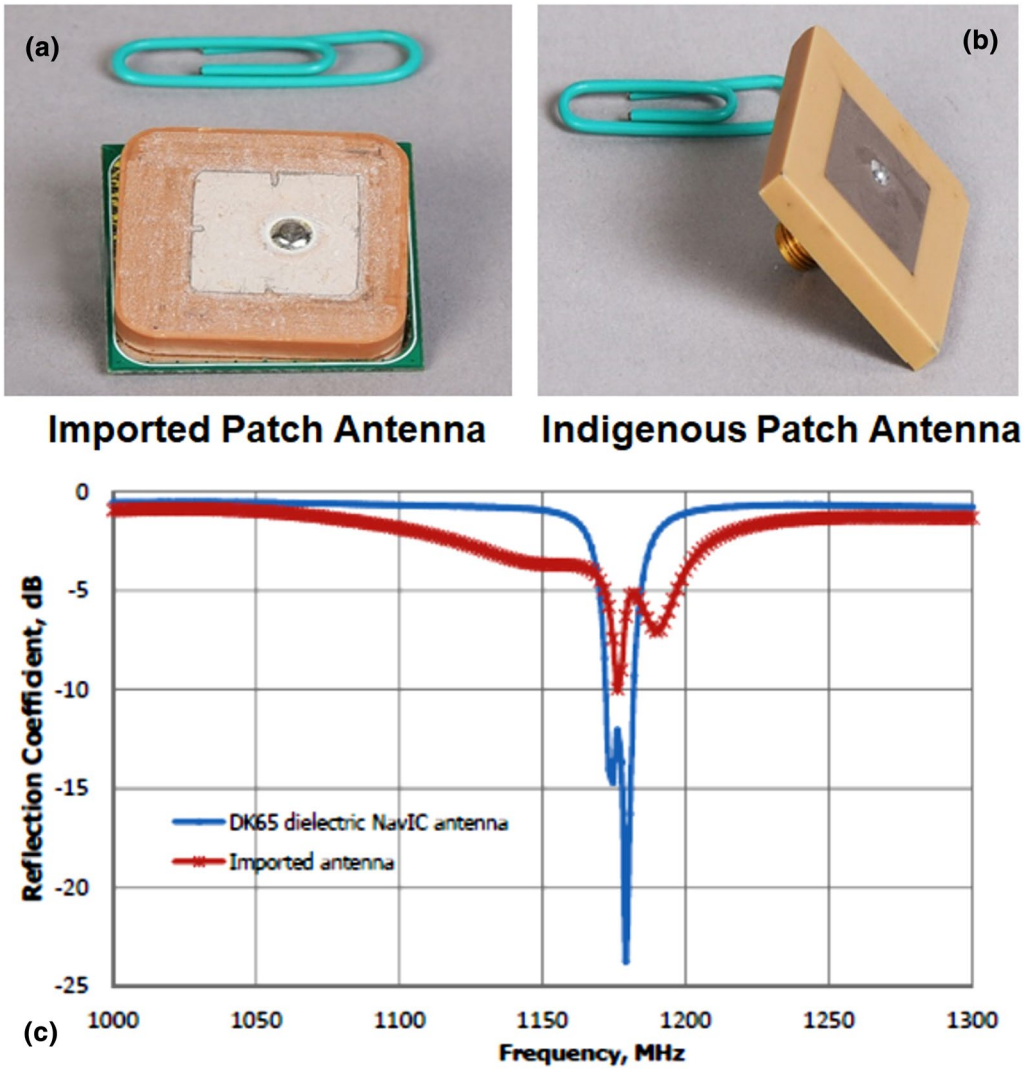

Figure 25: Imported and Indigenous patch antennas (top) for NAVIC Receiver and their responses (bottom).

materials have been used and latest bi-stage firing techniques were employed to get excellent properties. Figure 25 shows the photographs of imported and indigenous patch antennas for NAVIC Receiver and their responses.

12.4.3 YIG Composite for Microwave Circulator

Microwave devices for Satellite Communication need a number of passive components. The signal steering and isolation are carried out by devices called circulators, isolators etc. The heart of such devices are magnetic ceramics known as ferrites, which are imported in large numbers. Recently, ISRO has indigenously developed and successfully tested a yttrium-iron-garnet (YIG) composite for application in S-band. Critical control of composition and firing schedule are essential to achieve the desired performance. Indigenously developed components are at par with the imported component in performance. Figure 26 shows YIG composite for microwave circulator with blank of YIG composite processed as well as ultrasonically machined component extracted from the blank. The fractograph of the YIG composite is also presented. The circulator under qualification with 1 kW power as well as the performance characteristics of the processed composite are also presented.

12.4.4 Ultra-Low Expansion Glass–Ceramic (ULEGC)

Materials with near-zero thermal expansion are of great technological importance both

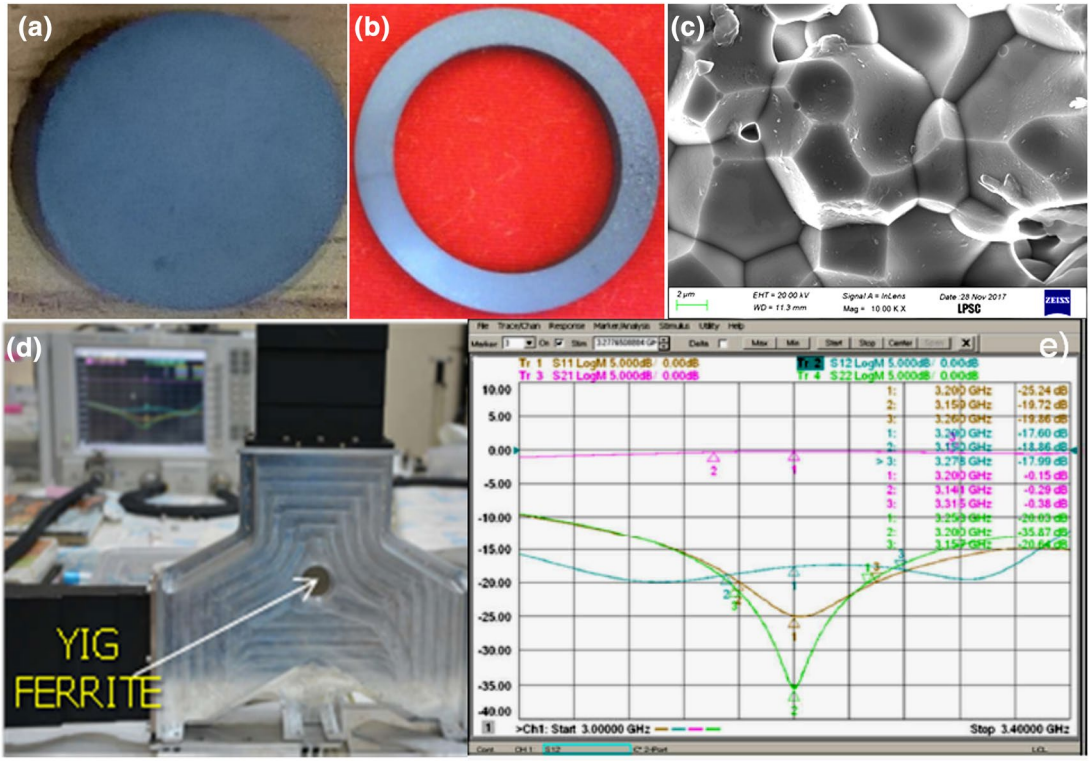

Figure 26: YIG composite for microwave circulator. **a** blank of YIG composite processed at 1150–1500 °C for 3 h, **b** ultrasonically machined component extracted from the blank, **c** Fractograph of the YIG composite, **d** circulator under qualification with 1 kW power and **e** the performance characteristics of the processed composite.

for commercial and strategic applications[84–87]. Ultra-low-expansion glass–ceramics lead this category and are used in satellite mirror, Ring Laser Gyroscope (RLG) and measurement platform. Processing and achieving the desired properties is a cutting-edge technology, still not mastered by many countries. India is still relying on import of such components for space and defense applications. ISRO has recently developed and tested ULEGCs by optimizing the composition, crystallization kinetics, and developed customized heat-treatment (both conventional and microwave-assisted). By suitably controlling the entire process, it was possible to make precipitated negative thermal expansion ceramics (~70%) in positive thermal expansion glass to achieve overall zero expansion in a wide range of temperature. These have been successfully tested in RLG and efforts to scale-up are in progress. Figure 27 presents the ultra low-expansion glass ceramics (ULEGC) processed by conventional crystallization and microwave crystallization. The figure also shows indigenously developed ULEGC under LASER glow-test for > 300 h and the variation of relative change in length with temperature of indigenous ULEGC showing nearly zero expansion in − 50 to + 400 °C.

13 Materials for Thermo-Structural Applications

RLVs experience severe aerodynamic and aerothermal environments during their ascent as well as descent. The environment is very severe during re-entry phase to the earth's atmosphere. Thermal protection system (TPS) materials provide a shield to the RLV against the extreme aerothermal loads. ISRO has successfully conducted Space Capsule Recovery Experiment (SRE) as a precursor to the RLV launches. The heat flux levels to which different parts of the outer surface of SRE experience are nose cap: 260 W/cm^2 where carbon–carbon composites are used; cone: 30–45 W/cm^2 and flare: 30–45 W/cm^2 where silica tiles are the choice and base: up to 25 W/cm^2 where flexible insulation is used. ISRO has successfully developed a set of TPS materials for SRE mission. Some of the TPS materials developed are given below:

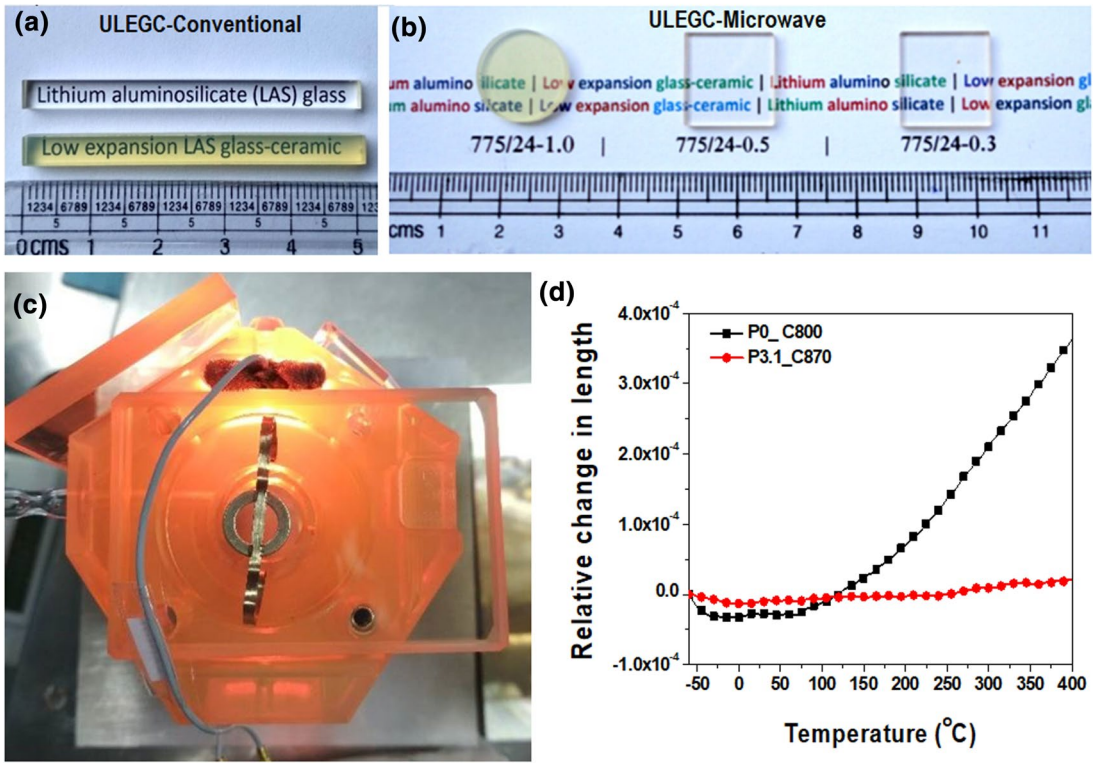

Figure 27: Ultra low-expansion glass ceramics (ULEGC) processed by conventional crystallization (**a**) and microwave crystallization (**b**). **c** Indigenously developed ULEGC under LASER glow-test for > 300 h and **d** the variation of relative change in length with temperature of indigenous ULEGC showing nearly zero expansion in − 50 to + 400 °C.

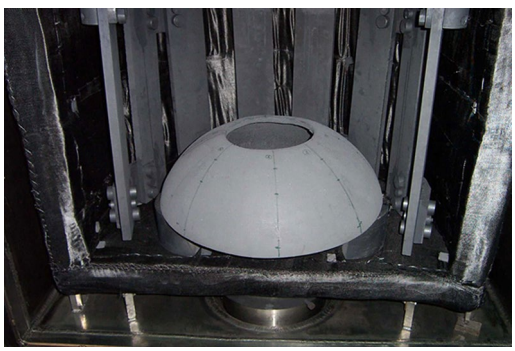

Figure 28: Carbon–carbon composite Dome with SiC coating as thermal protection systems for SRE.

13.1 Carbon–Carbon (C–C) Composites

Reinforced Carbon–Carbon (RCC) has very poor oxidation resistance and hence it must be given an oxidation resistant coating. The specific strength of carbon–carbon composite is around 0.17 GPa/g/cc. To provide oxidation resistance for reuse capability, an outer layer of silicon carbide is made over RCC. The RCC laminate is superior to a sandwich design because it is light in weight and rugged; and it promotes internal cross-radiation from the hot stagnation region to cooler areas, thus reducing stagnation temperatures and thermal gradients around the leading edge. The operating range of RCC is from minus 150 K to about 2000 K. The RCC is highly resistant to fatigue loading that is experienced during ascent and entry.

Fabrication of RCC starts with a rayon cloth graphitized and impregnated with a phenolic resin. This impregnated cloth is placed as a laminate for curing in an autoclave after which it is pyrolyzed to convert the resin to carbon. Subsequently, it is impregnated with furfural alcohol in a vacuum chamber, cured and pyrolyzed again to convert the furfural alcohol to carbon. This process is repeated thrice until the desired carbon–carbon properties are achieved. C–C composite used for nose cap and wing leading edges of RLV experience maximum temperature and heat flux. It is a thermo-structural material for prolonged use in the temperature range of 2000 K with a suitable oxidation protection

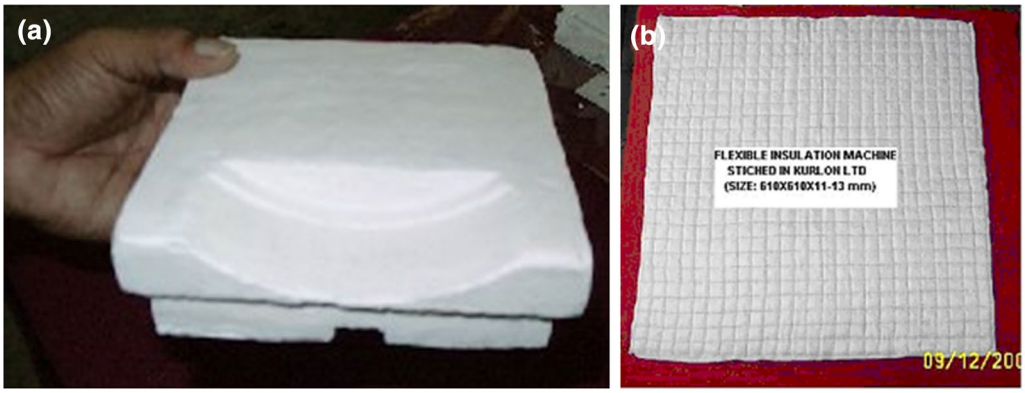

Figure 29: **a** Silica tile in machined condition and **b** flexible insulation.

Table 7: Thermo-physical properties of the developed tiles.

S. no.	Property	Value
Silica tiles		
1.	Density (g/cc)	0.25–0.32
2.	Tensile strength (kPa)	150 min
3.	Compressive strength, MPa	1.90–4.50
4.	Coefficient of thermal expansion, $x10^{-6}$ cm/cm deg.C [373–973 K]	0.48–0.52 (RT)
5.	Thermal conductivity, W/mK	0.06–0.07 (RT) 0.3 (at 1373 K)
6.	Porosity, %	70–80
7.	Emissivity-black tiles	0.80 min
8.	Flexural strength, MPa	1.20–1.90
Flexible insulation		
1.	Area	0.6 square meters
2.	Thickness	18–21 mm
3.	Density (g/m^2)	4700–5100
4.	Thermal conductivity, W/mK	0.028–0.034 [333–613 K]
5.	Emissivity	0.64
6.	Solar absorptance	0.20–0.23
7.	Maximum service temperature	800 K

coating, which is normally silicon carbide. C–C proto type nose cone for SRE has been realized by ISRO and is shown in Fig. 28. A multilayer SiC coating technology using pre-ceramic polymer blend has been standardized and brush coating/sintering trials on C–C prototype nose cone were successfully carried out.

13.2 Silica Tiles as Thermal Protection Materials

Silica tile is a versatile material for thermal protection system of re-entry vehicles in view of its optimum combination of thermo-physical properties[88]. Ideal choice of application of silica tiles is the temperature regime between 850 and 1400 K. Silica tiles possess low density, thermal conductivity, thermal expansion coefficient over the operating temperature range and

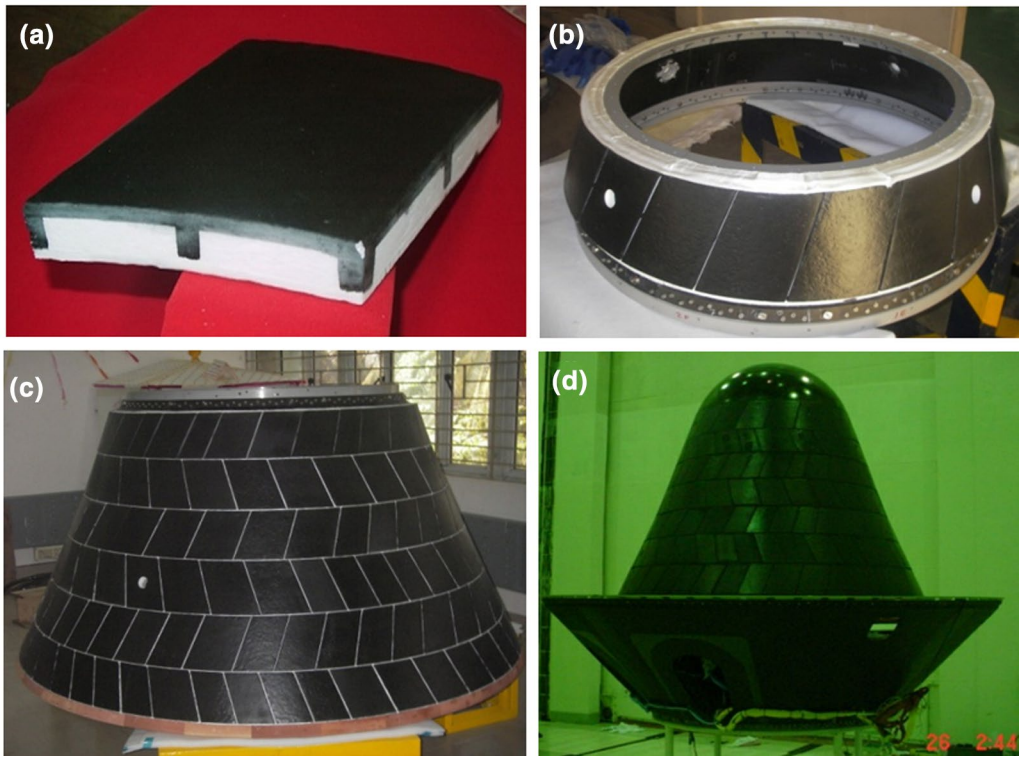

Figure 30: Photographs of a silica tile. **a** The silica tile (white in color) has been coated with a high emissivity coating; **b**, **c** silica tiles in different configurations on the hardware with the zig-zag layout with connecting joints and **d** fully integrated SRE module covered with silica tiles up to nose region. The nose part is made of carbon-phenolic ablative.

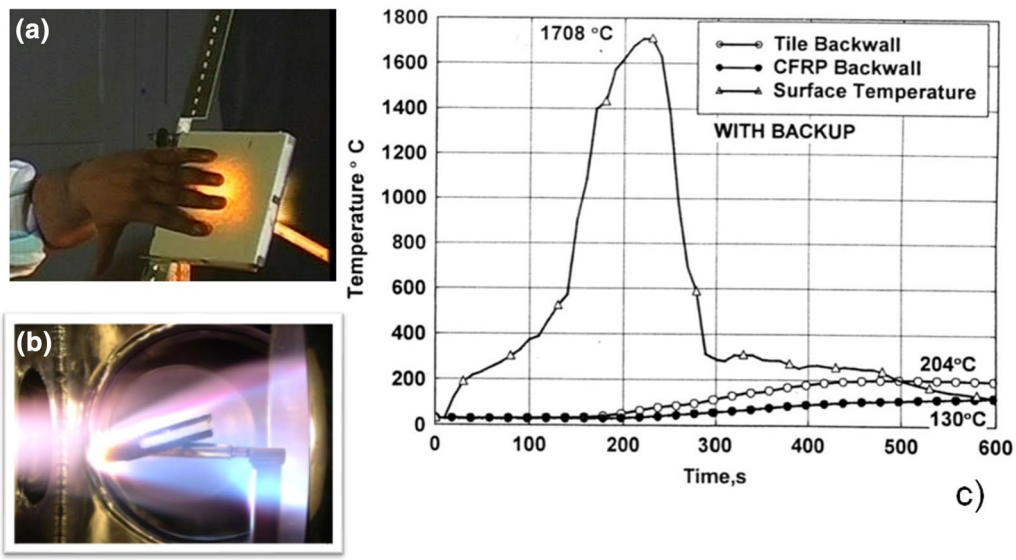

Figure 31: Photograph of a silica tile **a** showing a very low back-wall temperature that can make a person comfortably touch it with bare hand, when the other side is being heated with oxyacetylene torch; **b** silica tile undergoing heat flux test in a high enthalpy test facility and **c** thermal profile of a silica tile showing surface and back wall temperatures.

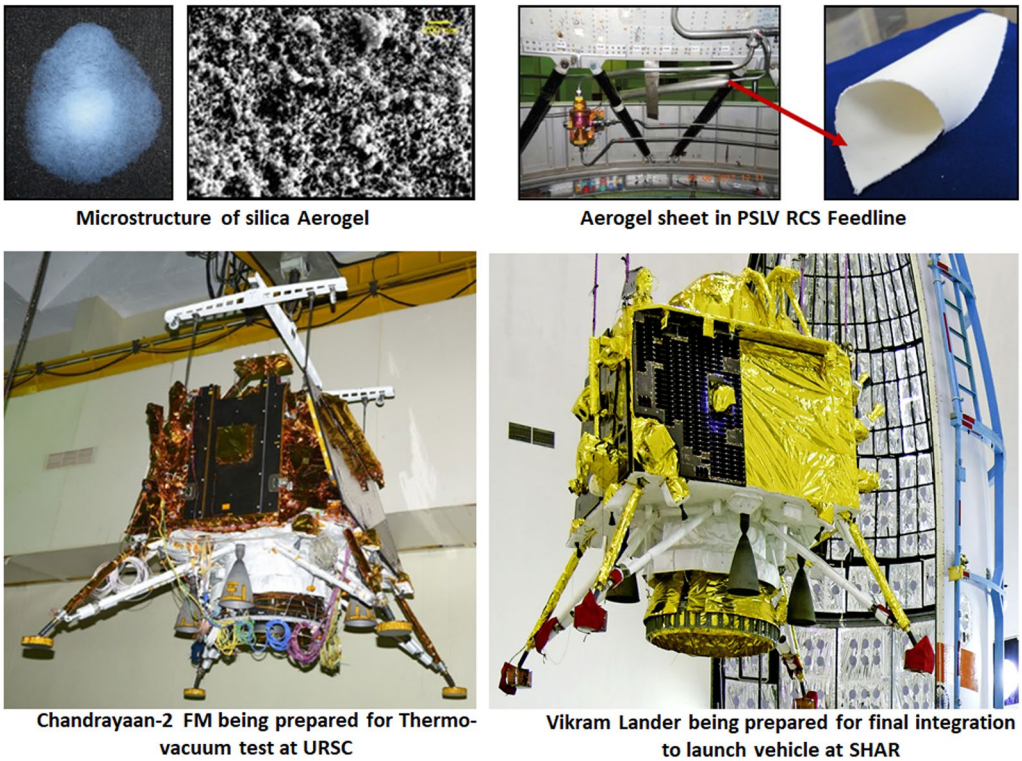
Microstructure of silica Aerogel
Aerogel sheet in PSLV RCS Feedline
Chandrayaan-2 FM being prepared for Thermo-vacuum test at URSC
Vikram Lander being prepared for final integration to launch vehicle at SHAR

Figure 32: photograph of silica aerogel and its microstructure; aerogel sheet used in PSLV-RCS feed line; aerogel sheets being used in Chandrayaan-2 flight model and Vikram lander being prepared for the final integration with launch vehicle at SDSC-Sriharikota.

high resistance to divitrification and thermal shock. The tile is composed of high silica fiber of 99% purity (min.) bonded with silica gel. A high emissivity black reaction cured borosilicate glass coating is applied on the surface of these tiles for re-radiating the heat efficiently during re-entry. ISRO has developed lab-scale process technology to make silica tiles. Subsequent to scale up studies and establishment of necessary processing facilities through industry interface on concurrent engineering mode, it has entered in the production phase and have been successfully used in SRE-1 and RLV-TD missions. The tile so developed machined to the desired contour is shown in Fig. 29a and that of flexible insulation blanket is presented in Fig. 29b. The thermo-physical properties of the developed tiles are given below in Table 7.

13.3 Silica Tiles from Laboratory to Flight

Silica tiles are the thermal protection materials for re-entry vehicles. Figure 30 shows various stages of integration of silica tiles to the flight hardware. Figure 30 shows the photograph of a silica tile coated with a high emissivity coating (Fig. 30a) along with the photographs of tiles in different configurations on the hardware with the zig-zag layout with connecting joints (Fig. 30b, c). The fully integrated SRE module is shown covered with silica tiles up to nose region is presented in Fig. 30(d). The nose part is made of carbon-phenolic ablative. Silica tiles have several unique properties and one of them is their very low thermal diffusivity. Figure 31 presents the photograph of a silica tile with a very low back-wall temperature that can make a person comfortably touch it with bare hand (Fig. 31a), when the other side is being heated with oxyacetylene torch. In case, during flight, the vehicle re-entry changes from streamline to turbulent flow, the tiles must withstand and therefore must be tested for the increased heat load. Figure 31c shows the testing of such a scenario. While the surface temperature is 1708 ^{o}C, the back wall temperature of a 22 mm thick tile shows a temperature much less than 50 ^{o}C during the peak heating. The photograph of a silica tile undergoing heat flux test in a high enthalpy test facility is also presented.

13.4 Silica Aerogels

Silica aerogel is one of the lightest material that has ever been developed. Due to its very low

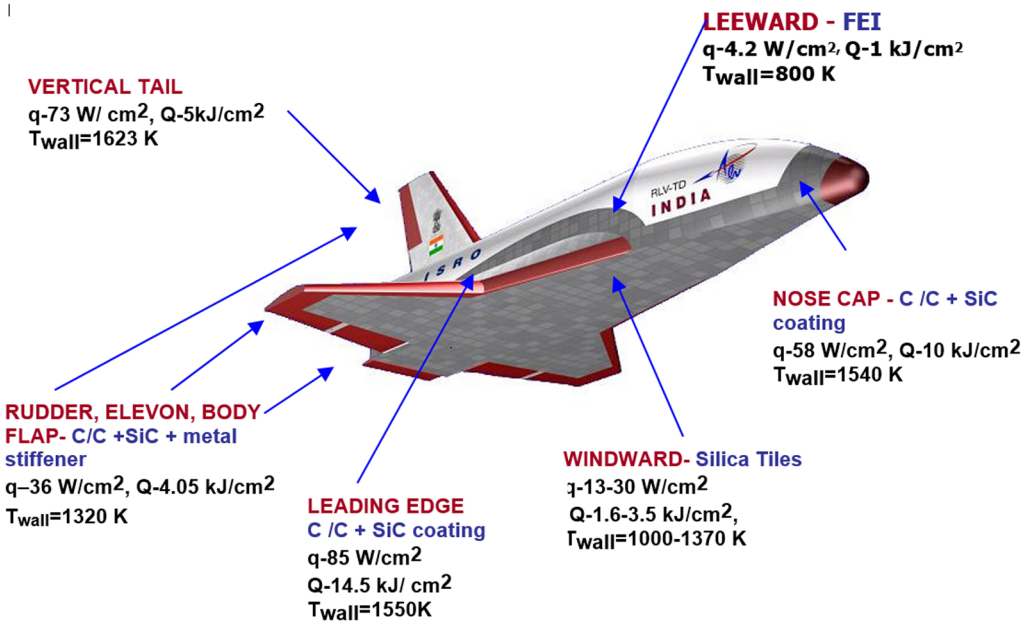

Figure 33: Schematic of a reusable launch vehicle along with the expected temperatures and flux during re-entry.

density, it possesses unique properties like very low thermal conductivity, low dielectric constant and good acoustic damping capacity[89–91]. Silica aerogel powder was used to make flexible aerogel sheets with several applications as shown. Figure 32 shows the photograph of silica aerogel and its microstructure along with aerogel sheet used in the reaction control system (RCS) of PSLV feed line, aerogel sheets being used in Chandrayaan-2 flight model and Vikram lander being prepared for the final integration with launch vehicle at SDSC-SHAR.

13.5 Flexible Reusable Surface Insulation (FRSI)

FRSI consists of a high temperature resistant, low thermal conductivity Alumina – Silica ceramic insulation felt sandwiched between an outer high silica cloth and an inner E-glass cloth. The entire assembly is stitched together using high temperature quartz sewing thread coated with polytetrafluroethylene. FRSI blankets are used on the leeward surface of RLV to protect regions of upper surface of the vehicle where temperature does not exceed 800 K. Figure 33 shows the schematic of a reusable launch vehicle along with the expected temperatures and flux during re-entry. The thermal inputs to the exterior of the re-usable launch vehicle are presented in the Fig. 33. ISRO has successfully established the processing technology of 610X610X11-13 mm FRSI blankets as shown in Fig. 29b. The thermo-physical properties of FRSI are included in Table 7.

13.6 Ultralight High-Performance C-Foam Based TPS

C-foam is an advanced, ultra-light, high performance TPS system with very low areal density (0.65–0.80 g/sq. cm for a panel thickness of 17 mm, density: ~ 0.35 g/cc). It can withstand temperatures up to 2500 °C. The TPS structure (Fig. 34) consists of reticulated open-cell C-foam core to provide majority of thermal insulation[92]. It is sandwiched by C/SiC CMC face sheet on front (hot) side to withstand aerodynamic or shear loads of reentry and single ply C–C composite face sheet on back (cool) side to accommodate bonding to vehicle structure. ISRO has successfully developed reticulated open-cell C-foam. Foam tiles of 200 × 200 × 20 mm size coated with SiC have been tested under kinetic heat flux conditions. Absolutely no degradation of structural integrity of the foam tiles occurred during the test.

14 Ceramics and Ceramic Composites

14.1 Carbon/Silicon Carbide Ceramic Matrix Composite

The silicon carbide matrix provides high modulus and oxidation resistance while the carbon fibres offer high temperature capability[93]. Because of its high specific strength and resistance to high temperature oxidation up to about

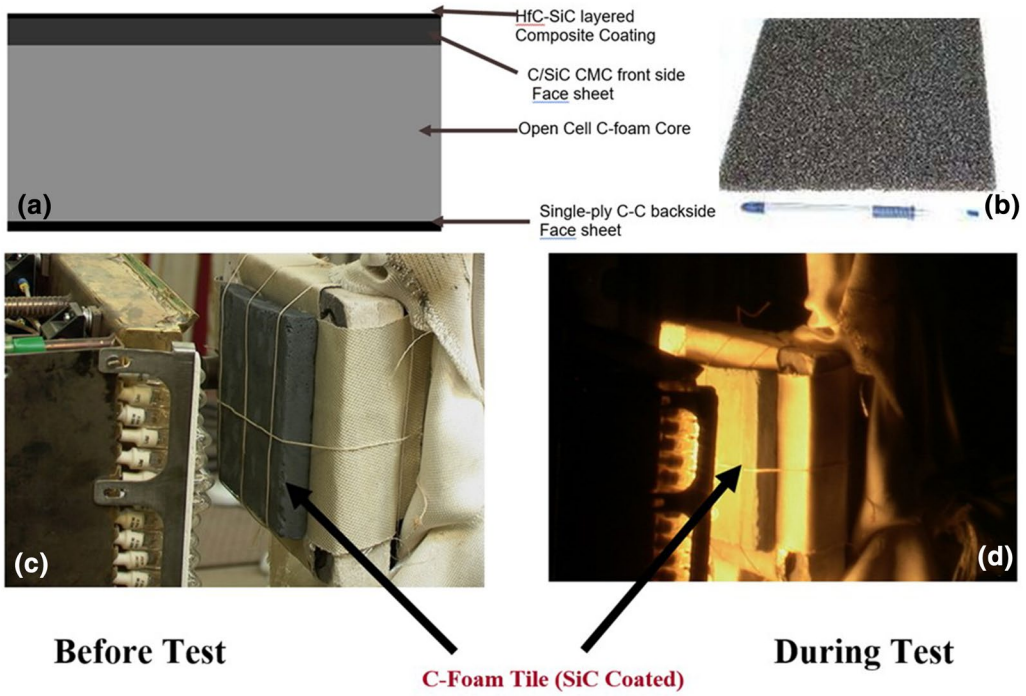

Figure 34: The ultra-high performance carbon foam based thermal protection system. The TPS structure consists of reticulated open-cell C-foam core to provide majority of thermal insulation. It is sandwiched by C/SiC CMC face sheet on front (hot) side to withstand aerodynamic or shear loads of re-entry and single ply C–C composite face sheet on back (cool) side to accommodate bonding to vehicle structure. Foam tiles of 200 × 200 × 20 mm size coated with SiC have been successfully tested under kinetic heat flux conditions.

1800 K, carbon/silicon carbide ceramic matrix composite is suitable for making the nose cap, leading edges, control surfaces etc. of reusable aerospace vehicles. Its specific strength is around 0.25 GPa/g/cc and specific modulus is about 45 GPa/g/cc. However, there are quite a few questions that remain unanswered such as those related to life prediction methods, repeatability, reliability, and mismatch between the fibre and the matrix in terms of respective coefficient of thermal expansion.

It is processed through a variety of methods such as Chemical Vapour Impregnation (CVI) to obtain high strength, Melt Infiltration (MI) for highest thermal conductivity and lowest porosity, and Polymer Infiltration Pyrolysis (PIP) for initial processing at low temperatures as well as for forming large complex shapes.

14.2 SiC/SiC Ceramic Matrix Composite

In these composites, the continuous fibre as well as the matrix is of silicon carbide. This CMC can thermally outperform superalloys. It has low density, high strength, inherent resistance to oxidation and creep-rupture resistance up to around 1600 K. Hence it can be used for making advanced hot structural components. It has a specific strength of about 0.3 GPa/g/cc and specific modulus in the vicinity of 75 GPa/g/cc. This type of CMCs are made by weaving or braiding small diameter SiC-based fibres in to 2D and 3D architectures. These fibres are coated by CVI technique, with interphase coatings based on boron nitride or carbon, either before or after architecture formation. SiC-based matrices are then infiltrated into these coated fibre architectures by different combinations of gas, polymer, slurry or molten silicon to obtain a densified composite[94].

SiC/SiC CMCs have insufficient long-term stability at high temperatures particularly in moist environments. Formation of complex-shaped components is also very cumbersome in view of the difficulty in fibre-weaving. Further the cost of the raw material and fabrication of the composite is very high.

Table 8: Metallic materials for spacecraft applications.

Materials	Sub-systems	Functional requirement
M250 Maraging steel	Fly wheel rim of Momentum wheel Assembly (MWA), Reaction wheel Assembly (RWA)	Speed 6000 RPM, High fatigue strength, Toughness
AISI 304 Stainless steel	Hysteresis Ring Holder and Magnet Spacer of DTG	Non- magnetic
17-4 PH stainless steel	Spur Gear, Pinion shaft of Solar Array Drive Assembly (SADA), and Pay load steering Mechanism (PSM)	High corrosion resistance, and high strength
AISI 440C	Inner spacer (DTG), Bearing components of MWA, RWA, stepper motor of SADA	High hardness, corrosion resistant, dimensionally stable
Ti-6Al-4V Ti alloy	Spindle, mounting case of DTG, Housing, main shaft of SADA, PSM, Gas bottles, LAM tanks	High Specific strength, Low temp properties corrosion resistance
AA6061, AA2024 Al. Alloys	Structural material, base plate for fly wheel MWA, SADA, PSM	Specific strength, dimensional stability
C-103 Nb alloy	Thrust chamber for AOCS, LAM	Heat and erosion resistance at > 1500 °C
Be/SiC	Scan mirrors	Highest Specific Modulus, Dimensionally stable, Radiation resistance

14.3 Ultra-High Temperature Ceramics (UHTC)

Thermal protection systems based on high temperature ceramics such as zirconium diboride (ZrB_2) and hafnium diboride (HfB_2) with or without silicon carbide appear to be very promising for realizing leading edges and nose cap of RLVs in future. These materials can withstand temperatures up to 3000 K[95]. Powder metallurgical processing technologies have been successfully established in ISRO for processing these ceramics.

15 Materials for Spacecraft Applications

Material selection for spacecraft applications is limited by effects of space on materials. Some of the problems in space are degradation due to radiation and thermal cycling (− 160 to 180 °C), presence of atomic oxygen in low earth orbits, sublimation and evaporation at high vacuum in space ($> 10^{-12}$ torr), cold welding in a frictionless atmosphere, sub-zero conditions during solar eclipse periods and high velocity particles. General practices include avoidance of the use of metals such as Sn, Zn and Cd, plating or coating of Mg parts to avoid sublimation, materials prone for cold welding be plated or coated with $MoSi_2$ and usage of FCC materials for parts exposed to cryogenic conditions. Table 8 presents various metallic materials for spacecraft applications.

Silicon carbide (SiC) is an important material for several technological applications, including mirrors in space based optics. The mirror blanks of SiC are produced either by a chemical vapour deposition (CVD) process or by sintering of powders. While CVD is a slow and cumbersome process, powder processing is challenging from the point of difficulties in attaining full density without sintering additives. Using aluminium nitride and aluminium nitride + yttria as a sintering aids and keeping the total volume fraction of additives below 4%, SiC could be successfully sintered at 1900 °C and the polishability to the required optical finish were successfully demonstrated along with other physical and mechanical properties[96].

16 Five Decades of Materials Development Activities in ISRO: Future Goals

The past five decades of materials development activities in ISRO have resulted in technologies that have successfully propelled ISRO launch vehicle and satellite programs. What has started as a small group of motivated materials researchers with threadbare facilities grew to a giant aerospace materials research laboratory that has created infrastructure, both in-house and outside ISRO, and developed aerospace quality materials meeting the challenges of designers. Over the past five decades, large number of sophisticated, state of the art experimental facilities have been established that cater to the material development activities. During the initial phase of launch vehicle program, industries were in a nascent stage, essentially catering to routine domestic requirements, not tuned for production of aerospace grade materials. This necessitated VSSC taking up both the laboratory scale development work

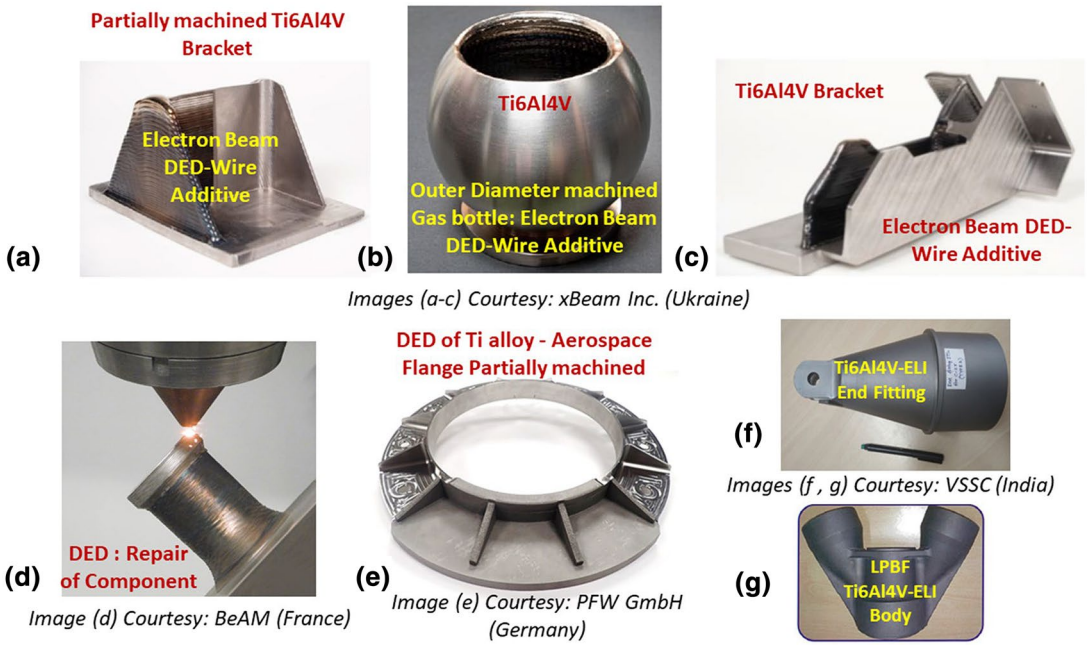

Figure 35: Few Ti alloy components made through different AM processes- Electron beam-DED- Wire additive manufacturing technique—**a** partially machined Ti6Al4V bracket, **b** outer diameter machined Ti6Al4V gas bottle, **c** machined Ti6Al4V bracket, **d** repair of a component using DED process, **e** near-net shaped Ti6Al4V flange for aerospace application partially machined, **f** Ti6Al4V-ELI End fitting component and **g** Ti6Al4V-ELI body component made through LPBF process. Images reproduced with permission from: **a**–c xBeam Inc. (Ukraine), **d** BeAM, (France), **e** Hutchinson PFW Aerospace GmbH (Germany) and **f**, **g** VSSC (India)[36].

and subsequent scaling up of activities to realize the vehicle systems. However, the last three decades saw significant growth in the infrastructural facilities in the country for processing of various types of metallic materials. Slowly the Indian industry has acquired the know-how by hand holding with ISRO and has matured to deliver materials on demand, meeting aerospace quality requirements.

The present demands of space program include lower-costs for materials and faster realization of rocket systems that have prompted reusability of vehicle structures as well as disruptive technologies such as additive manufacturing which are gaining momentum. Research and development in this direction is underway currently and it is intended to induct these technologies in to the ISRO launch vehicle program, in the coming years. The manned space flight program of ISRO, Gaganyaan has taken the material quality control to a more stringent level. Type testing of materials meeting the human rating requirements of launch vehicle structures for Gaganyaan program, is underway.

16.1 Additive Manufacturing

Conventional manufacturing techniques involving casting, forming, forging rolling and machining are the common manufacturing processed used for the realization of aerospace components. These are top-down approaches meaning that the component is carved out of a block and significant wastage of material is inevitable in these processes. The launch vehicle structures are fabricated through metal joining processes such as welding, brazing and riveting processes. The high buy-to-fly ratio in the conventional manufacturing processes leads to both cost and lead time disadvantages. Near-net shape forming/forging technologies like closed die forgings, shaped forgings/rings, can improve the buy-to-fly ratio. Further, material joining processes involving different types of materials in complex rocket engines lead to reduced levels of inspectability to detect defects and thereby reducing the overall reliability of systems. These limitations of the conventional manufacturing processes have been overcome by the additive manufacturing (AM) process wherein a bottom-up approach is used for component fabrication. In AM, the

materials for fabrication could either be in powder or wire form and the heating source can be either laser, electron beam or plasma arc and the components are built layer-by-layer. Using metal AM processes such as laser powder bed fusion or directed energy deposition, complex components have been successfully realized and their performance is being evaluated. ISRO has started implementing the additive manufacturing technologies through extensive technology development studies on several aerospace materials such as Inconel-718, Ti6Al4V-ELI, AISI 316L, AlSi10Mg and 17-4 PH and is now matured to realize launch vehicle components from these materials successfully[97–99]. Many technology development projects are in progress at ISRO to implement different technologies for realizing structural and functional materials. Figure 35 shows some of the Titanium alloy components made through different AM processes.

16.2 Development of Solid Rocket Motor Casings Through Flow Forming

Large diameter ($\phi \sim 3$ m and several meters in length) solid rocket boosters for PSLV and GSLV are realized through roll bending of 8 mm thick maraging plates welded longitudinally to form shells and these are joined circumferentially to different shells/rings/domes. Several meters of welding is involved for each pass and usually, these are multi-pass welded, up to 4 passes. After each weld pass, non-destructive inspection is conducted and if defects are detected, approved repair schemes are implemented. Therefore, welding route to realize these motor cases is cumbersome and time taking leading to cost and time disadvantages. ISRO has been attempting to implement flow forming technology for the fabrication of solid rocket motor segments made from 0.3%C-CrMoV (ESR) steel and shells have been successfully formed and are under evaluation. It is expected that flow formed segments would soon replace the welded segments in the Indian launch vehicles.

16.3 Development of Aluminium–Lithium Alloys

Presently aluminium alloy AA 2219 is used for the fabrication of propellant tanks of both earth-storable and cryogenic tanks, as this alloy is compatible with fluids (UDMH and N2O4 for earth storable stages as well as LH2 and LOX for cryogenic stage) and retains its mechanical properties with decreasing temperature down to 20 K. However, weld efficiency of AA 2219 is very low and therefore, the weight of these propellant tanks is high. However, the third generation Al-Cu-Li alloys like AA 2050, AA 2195 and AA2198 have been successfully used for the cryogenic propellants tanks. However, the processing of Lithium containing aluminium alloys needs dedicated facilities and cannot be processed along with other grades of aluminium alloys. There is no dedicated cast house for processing these alloys currently in India. With improved modulus, reduced density and increased weld efficiency, aluminium–lithium alloys will provide significant payload advantages over AA 2219 for propellant tank applications.

17 Summary

Successes in aerospace science and technology are directly related to the success in development and realization of engineering materials in the desired forms and conditions. Innovations and improvements to the existing aerospace systems are often limited by the availability of engineering materials with the desired properties. The necessity to develop materials which can perform well in severe operating environments is a major challenge for materials scientists, and it requires a fundamental understanding of material response under extreme conditions of heat flux, stresses, strain rates, and corrosive environments, such as those experienced in rocket engines. Materials processing technologies are infrastructure sensitive unlike many other areas of research and are cost and time intensive. Therefore, proper planning is essential to initiate activities where new materials systems are envisaged. System designers need to spell out material requirements *apriori*, so that developmental activities can be initiated well in advance and progressed to meet the time schedules.

Multi-metallic systems have been extensively utilized and are an important part of successes in ISRO's launch vehicle and satellite programs. Varieties of materials have been conceptualized, produced and successfully implemented in Indian launch vehicle and space craft as per the design requirements. Over past four decades, ISRO has set-up a sound base in-house as well as in the industries in the country, for the development of a variety of metallic and non-metallic materials and products for Indian space programs. Outstanding accomplishments in materials, to a large extent, have made possible the major advances in Indian space activities. The emerging advanced space programs of ISRO

wherein reusable launch vehicles (RLVs) are the major component, pose formidable challenges with respect to the development of thermal protection and thermo-structural materials. While ceramics will meet these requirements in short term, advanced trends in TPS such as ultralight multilayer C-foam, TiAl intermetallics, multiwall metallic and smart structures and nanomaterials embedded composites, will require greater attention from material scientists to meet the long-term objectives of a sturdier and light weight TPS.

Continuous research on advanced space materials has led to the indigenization of a number of strategic materials making country self-reliant saving foreign exchange. State of the art facilities have been established in the past forty years in different parts of the country for materials processing and fabrication of space structures. Various materials related technologies have been transferred to Industries for production. ISRO is ready to take up any challenges on innovations in materials.

Finally, it would be prudent to acknowledge the enormous contributions by the material scientists of ISRO who had neither prior experience nor know-how on how to develop these materials in first place. Self-motivation, spirit of cooperation, intuitive skills, value judgement, ability to take failures in their stride, open discussions and respect for other's opinions, all being the hallmarks of ISRO family of researchers, are the epitome of the success of materials development activities. It is heartening to note that the past five decades of materials research activities have been very successful and the progress achieved so far certainly paves way for the future launch vehicle programs of India.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Acknowledgements

Authors sincerely wish to thank their colleagues at Vikram Sarabhai Space Centre, Trivandrum for their incredible commitment in realizing space materials and making India self-reliant in a number of material systems for space applications. They wholeheartedly acknowledge each and every researcher, who has contributed to the success of materials development. They thank Director, VSSC for his kind permission for publishing this work.

Declarations

Conflict of interest

The authors of this manuscript certify that they have NO affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Received: 31 July 2021 Accepted: 29 December 2021
Published online: 09 February 2022

References

1. Suresh BN, Sivan K (2015) Integrated design for space transportation system. Springer Nature, Berlin
2. Suseelan-Nair K, Sinha PP (2009) Evolution of materials research for Indian space programmes. ISRO Head quarters, Bangalore
3. Shukla AK, Sharma VMJ, Narayana-Murty SVS, Ramesh-Narayanan P, Sharma SC (2014) Integrity of structural and thermo-structural materials for indian space programme. Procedia Eng 86:8–17
4. Gupta RN, Raja VS, Mukherjee MK, Narayana-Murty SVS (2017) On improving the quality of gas tungsten arc welded 18Ni 250 maraging steel rocket motor casings. Metall Mater Trans A 48:4655–4666
5. Chakravarthi KVA, Koundinya NTBN, Sarkar A, Narayana-Murty SVS, Nageswara-Rao B (2018) Optimization of hot workability and control of microstructure in 18Ni (M250 Grade) maraging steel using processing maps. ASTM Mater Perform Character 7:547–561
6. Sundaresan S, Manirajan M, Rao BN (2010) On the fracture toughness evaluation in weldments of a maraging steel rocket motor case. Mater Des 31:4921–4926
7. Singaravelu J, Sundaresan S, Rao BN (2013) Application of fracture mechanics to specify the proof load factor for clamp band systems of launch vehicles. J Mater Eng Perform 22:926–935
8. Ghosh BR, Murthy MSP, Sharma SC, Mittal MC, Nagarajan KV (1987) TIG welding Technology of 7mm thick 18 Ni 250 grade maraging steel plates for space applications. Trans Indian Inst Metals 40:227–234
9. Chakravarthi KVA, Koundinya N, Narayana-Murty SVS, Sivakumar D, Nageswara-Rao B (2018) Optimization of hot workability and control of microstructure in CF250 grade cobalt-free maraging steel: an approach using processing maps. Metallogr Microstruct Anal 7:35–47
10. Narayana-Murty SVS, Sreekumar K, Natarajan A, Sinha PP (1997) Metallographic investigations on the appearance of streaks in radiographic inspection of maraging steel forged ring-plate weldments. In: Proceedings of the international conference on advanced metallurgical processes, New Age International Pvt. Limited, pp 1399–1404

11. Narayana-Murty SVS, Sudarsana-Rao G, Venugopal A, Ramesh-Narayanan P, Sharma SC, George KM (2014) Metallurgical analysis of defects in the weld joints of large-sized maraging steel rocket motor casing. Metallogr Microstruct Anal 3:433–447
12. Nageswara-Rao M, Narayana-Murty SVS (2020) Hot deformation of 18% Ni maraging steels: a review. Mater Perform Character 8:742–765
13. Ramesh-Narayanan P, Sreekumar K, Natarajan A, Sinha PP (1990) Metallographic investigations of the heat-affected zone II/parent metal interface cracking in 18Ni maraging steel welded structures. J Mater Sci 25:4587–4591
14. Manwatkar SK, Narayana-Murty SVS, Narayanan PR, Sharma SC, Venkitakrishnan PV (2016) Stress corrosion cracking of a maraging steel shear bolt used in the interstage structure of a satellite launch vehicle. Metallogr Microstruct Anal 5:411–420
15. Beena AP, Sundaresan MK, Rao BN (1995) Destructive tests of 15CDV6 steel rocket motor cases and their application to lightweight design. Int J Press Vessels Pip 62:313–320
16. Ghosh R, Venugopal A, Karthikeyan MK, Narayanan PR, Pant B, Cherian RM (2018) Corrosion and nanomechanical behavior of high strength low alloy steels. Mater Corros 69:926–932
17. Manikandan S, Mishra AK, Nayak G, Narayana-Murty SVS, Rao GS, Narayanan PR, Ram-Kumar P, Venkitakrishnan PV (2018) Residual strength and fracture toughness of 0.3 C-CrMoV (ESR) ultrahigh-strength steel used for solid booster motor cases. Mater Perform Character 7:365–375
18. Ramkumar P, Gupta RK, Anil-Kumar V, Muthupandi V (2021) Effect of pre- and post weld heat treatment on microstructure development and mechanical properties of 0.3%C-CrMoV (ESR) high-strength low-alloy steel. J Mater Eng Perform. https://doi.org/10.1007/s11665-021-05929-4
19. Ramkumar P, Anil-Kumar V, Gupta RK, Karthikeyan MK, Narahari-Prasad S, Gino-Prakash F, Chakravarthi KVA, Maruthi-Prasad Y, Venkitakrishnan PV (2017) Melting and thermomechanical processing of high strength 0.3%C–CrMoV (ESR) steel. Trans Ind Inst Met 71:1475–1485. https://doi.org/10.1007/s12666-018-1283-2
20. Narayana-Murty SVS, Manwatkar SK, Ramesh-Narayanan P (2015) Role of metallographic analysis in the identification of location of crack initiation in a burst tested AA 2219 propellant tank. Metallogr Microstruct Anal 4:392–402
21. Jha AK, Narayana-Murty SVS, Divakar V, Sreekumar K (2003) Metallurgical analysis of cracking in the weldment of propellant tank. Eng Fail Anal 10:265–273
22. Ghosh R, Venugopal A, Sankaravelayudham P, Panda R, Sharma SC, George KM, Raja VS (2015) Effect of thermomechanical treatment on the environmentally induced cracking behavior of AA7075 alloy. J Mater Eng Perform 24:545–555
23. Venugopal A, Sreekumar K, Raja VS (2010) Effect of repair welding on electrochemical corrosion and stress corrosion cracking behaviour of TIG welded AA2219 aluminum alloy in 3.5% NaCl solution. Meatll Mater Trans A 41:3151–3160
24. Sarkar A, Saravanan K, Nayan N, Narayana-Murty SVS, Ramesh-Narayanan P, Venkitakrishnan PV, Mukhopadhyay J (2017) Microstructure and mechanical properties of cryorolled aluminum alloy AA2219 in different thermomechanical processing conditions. Metall Mater Trans A 48:321–341
25. Manwatkar SK, Sunil M, Prabhu A, Narayana-Murty SVS, Joseph R, Narayanan PR (2019) Effect of grain size on the mechanical properties of aluminum alloy AA2219 parent and weldments at ambient and cryogenic temperature. Trans Indian Inst Met 72:1515–1519
26. Manikandan P, Prabhu TA, Manwatkar SK, Rao GS, Narayana-Murty SVS, Sivakumar D, Pant B, Mohan M (2021) Tensile and fracture properties of aluminium alloy AA2219-T87 friction stir weld joints for aerospace applications. Metall Mater Trans A. https://doi.org/10.1007/s11661-021-06337-y
27. Nayan N, Narayana-Murty SVS, Jha AK, Pant B, Sharma SC, George KM, Sastry GVS (2013) Processing and characterization of Al-Cu-Li alloy AA2195 undergoing scale up production through vacuum induction melting technique. Mater Sci Eng A 576:21–28
28. Nayan N, Narayana-Murty SVS, Jha AK, Pant B, Sharma SC (2014) Koshy M George, "Mechanical properties of aluminium–copper–lithium alloy AA2195 at cryogenic temperatures." Mater Des 58:445–450
29. Nayan N, Narayan-Murty SVS, Chhangani S, Prakash A, Prasad MJNV, Samajdar I (2017) Effect of temperature and strain rate on hot deformation behavior and microstructure of Al-Cu-Li alloy. J Alloy Compd 723:548–558
30. Nayan N, Mishra S, Prakash A, Sarkar R, Narayana-Murty SVS, Yadava M, Prasad MJNV, Samajdar I (2019) Origin of through-thickness serrated tensile flow behavior in Al–Cu–Li (AA2195) alloy: effect of microstructure and texture. Materialia 5:100180
31. Nayan N, Mishra S, Prakash A, Narayana-Murty SVS, Prasad M, Samajdar I (2019) Effect of cross-rolling on microstructure and texture evolution and tensile behavior of aluminium-copper-lithium (AA2195) alloy. Mater Sci Eng, A 740:252–261
32. Nayan N, Yadava M, Gurao NP, Narayana-Murty SVS, Mahesh S, Prasad MJNV (2020) Sub-zero temperature dependence of tensile response of friction stir welded Al-Cu-Li (AA2198) alloy. Metall Mater Trans A 51:1173–1182
33. Nayan N, Narayana-Murty SVS, Sarkar R, Mukhopadhyay AK, Ahlawat S, Prasad MJNV, Samajdar I (2019) The anisotropy of serrated flow behavior of Al-Cu-Li (AA2198) alloy. Metall Mater Trans A 50:5066–5078

34. Nayan N, Mukhopadhyay AK, Narayana-Murty SVS, Yadava M, Sarkar R, Prasad MJNV, Samajdar I (2020) Effect of Cu and Li contents on the serrated flow behavior of Al-Cu-Li based alloys. Metall Mater Trans A 51:1457–1462
35. Nayan N, Narayana-Murty SVS, Mukhopadhyay AK, Prasad KS, Jha AK, Pant B, Sharma SC, George KM (2013) Ambient and cryogenic tensile properties of AA2195T87 sheets with pre-aging cold work by a combination of cold rolling and stretching. Mater Sci Eng A 58:475–479
36. Kumar VA, Gupta RK, Prasad M, Narayana-Murty SVS (2021) Recent advances in processing of titanium alloys and titanium aluminides for space applications: a review. J Mater Res 36:689–716
37. Gupta RK, Anil-Kumar V, Chhangani S (2016) Study on variants of solution treatment and aging cycle of titanium alloy Ti6Al4V. J Mater Eng Perform 25:1492–1501
38. Manikandan P, Rao GS, Muneshwar P, Narayana-Murty SVS, Narayanan PR (2019) Tensile and fracture properties of commercially pure titanium (CP-70) hemispherical forgings. Trans Indian Inst Met 72:1469–1473
39. Gupta RK, Anil-Kumar V, Roshan-Xavier X (2018) Mechanical behavior of commercially pure titanium weldments at lower temperatures. J Mater Eng Perform 27:2192–2204. https://doi.org/10.1007/s11665-018-3307-9
40. Gupta RK, Anil-Kumar V, Ram-Kumar P (2016) Effect of multiple step thermo-mechanical working and recrystallization annealing on mechanical properties and microstructure in titanium alloy Ti6Al4V closed die forgings. J Mater Eng Perform 25:2551–2562
41. Kumar VA, Sarkar A, Gupta RK, Prasad M, Narayana-Murty SVS (2021) Microstructure evolution during high-temperature deformation of Ti-5Al-5V-2Mo-1Cr-1Fe alloy under compression. J Mater Eng Perform 30:3258–3272
42. Anil-Kumar V, Narayana-Murty SVS, Gupta RK, Babu RR, Prasad M (2015) Melting and microstructure analysis of β-Ti Alloy Ti–5Al–5Mo–5V–1Cr–1Fe with and without boron. Trans Indian Inst Met 68:207–215
43. Gupta RK, Narayana-Murty SVS, Pant B, Agarwala V, Sinha PP (2012) Hot workability of γ+α2 titanium aluminide: development of processing map and constitutive equations. Mater Sci Eng A 551:169–186
44. Gupta RK, Anil-Kumar V, Ramesh-Babu R, Gourav-Rao A (2017) Development of ductile $\gamma + \alpha_2$ Titanium Aluminide Ti-Al-Cr-Nb-B alloy through ingot metallurgy route and its characterization. Mater Sci Eng A 703:124–136
45. Anoop CR, Singh RK, Kumar RR, Jayalakshmi M, Antony-Prabhu T, Thomas-Tharian K, Narayana-Murty SVS (2021) A review on steels for cryogenic applications. Perform Character 10:16–88
46. Anoop CR, Singh RK, Kumar RR, Jayalakshmi M, Narayana-Murty SVS, Tharian KT (2020) Development and validation of processing maps for hot deformation of modified AISI 321 austenitic stainless steel. Mater Perform Character 9:150–169
47. Anoop CR, Prakash A, Narayana-Murty SVS, Samajdar I (2018) Origin of low temperature toughness in a 12Cr-10Ni martensitic precipitation hardenable stainless steel. Mater Sci Eng, A 709:1–8
48. Anoop CR, Prakash A, Narayana-Murty SVS, Samajdar I (2018) Effect of zener-holloman parameter on the prior austenite grain size in a 12Cr-10Ni precipitation-hardenable stainless steel. J Mater Eng Perform 27:3559–3565
49. Anoop CR, Prakash A, Giri SK, Narayana-Murty SVS, Samajdar I (2018) Optimization of hot workability and microstructure control in a 12Cr-10Ni precipitation hardenable stainless steel: an approach using processing maps. Mater Charact 141:97–107
50. Manikandan P, Rao GS, Saravanan K, Chakravadhanula VSK, Amruth M, Narayana-Murty SVS, Sharma VMJ, Ramesh-Narayanan P (2019) High temperature tensile behavior of a nickel-based superalloy 55Ni-17Cr-12Fe-9Mo-2Nb-1.5 Al used in launch vehicle applications. J Mater Eng Perform 29:377–390
51. Gupta RK, Anil-Kumar V, Sukumaran A, Kumar V (2018) High-temperature tensile behavior of base metal and electron beam-welded joints of Ni-20Cr-9Mo-4Nb superalloy. Metall Mater Trans A 49:2654–2672. https://doi.org/10.1007/s11661-018-4652-x
52. Jalaja K, Chakravadhanula VSK, Manwatkar SK, Narayana-Murty SVS (2021) Microstructural characterization of XH 67 nickel-based superalloy under different heat treatment conditions. Metallogr Microstruct Anal 10:257–265
53. Saravanan K, Chakravadhanula VSK, Manwatkar SK, Narayana-Murty SVS, Ramesh-Narayanan P (2020) Dynamic strain aging and embrittlement behavior of IN718 during high-temperature deformation. Metall Mater Trans A 51:5691–5703
54. Krishna SC, Rao GS, Singh SK, Narayana-Murty SVS, Venkatanarayana G, Jha AK, Pant B, Venkitakrishnan PV (2016) Processing and characterization of sub-delta solvus forged hemispherical forgings of inconel. J Mater Eng Perform 25:5477–5485
55. Krishna SC, Agilan M, Sudarasana-Rao G, Singh SK, Narayana-Murty SVS, Narayana GV, Beena AP, Rajesh L, Jha AK, Pant B (2017) Design, development and testing of inconel alloy IN718 spherical gas bottle for oxygen storage. J Mater Eng Perform 26:5355–5365
56. Prasad KS, Panda SK, Kar SK, Narayana-Murty SVS, Sharma SC (2018) Prediction of fracture and deep drawing behavior of solution treated Inconel-718 sheets: numerical modeling and experimental validation. Mater Sci Eng A 733:393–407

57. Prasad KS, Panda SK, Kar SK, Narayana-Murty SVS, Sharma SC (2018) Effect of solution treatment on deep drawability of IN718 sheets: experimental analysis and metallurgical characterization. Mater Sci Eng, A 727:97–112
58. Prasad KS, Panda SK, Kar SK, Sen M, Narayana-Murty SVS, Sharma SC (2017) Microstructures, forming limit and failure analysis of inconel 718 sheets for fabrication of aerospace components. J Mater Eng Perform 26:1513–1530
59. Anil-Kumar V, Gupta RK, Narayana-Murty SVS, Prasad AD (2016) Hot workability and microstructure control in Co20Cr15W10Ni cobalt-based super alloy. J Alloy Compd 676:527–541
60. Gupta RK, Anil-Kumar V (2017) Studies on similar and dissimilar metal EBW joints of Fe-31Ni-5Co and Co-20Cr-15W-10Ni alloys. J Mater Eng Perform 26:2963–2973
61. Sarkar A, Narayana-Murty SVS, Prasad MJNV (2020) Dynamic recrystallization in Cu-Cr-Zr-Ti alloy under large plane strain conditions. Metall and Mater Trans A 51:4742–4752
62. Sudarsana-Rao G, Srinath J, Raman SGS, Sharma VMJ, Narayana-Murty SVS, Ramesh-Narayanan P, Venkitakrishnan PV (2017) Effect of temperature on low cycle fatigue behavior of annealed Cu-Cr-Zr-Ti alloy in argon atmosphere. Mater Sci Eng-A 692:156–167
63. Sarkar A, Prasad MJNV, Narayana-Murty SVS (2020) Effect of initial grain size on hot deformation behaviour of Cu-Cr-Zr-Ti alloy. Mater Charact 160:110112
64. Narayana-Murty SVS, Manwatkar SK, George M, Narayanan PR (2016) Microstructural analysis of a failed Cu-Cr-Ti-Zr thrust chamber liner of a cryogenic engine. Mater Perform Character 5:648–663
65. Shukla AK, Narayana-Murty SVS, Suresh-Kumar R, Mondal K (2013) Effect of powder milling on mechanical properties of hot-pressed and hot-rolled Cu–Cr–Nb alloy. J Alloy Compd 580:427–434
66. Shukla AK, Samuel MG, Suresh-Kumar R, Narayana-Murty SVS, Mondal K (2013) Effect of powder oxidation on densification and properties of vacuum hot pressed Cu–Cr–Nb alloy. Mater Sci Eng A 561:452–459
67. Shukla AK, Narayana-Murty SVS, Sharma SC, Mondal K (2014) "Aging behavior and microstructural stability of a Cu-8Cr-4Nb alloy. J Alloy Compd 590:514–525
68. Shukla AK, Narayana-Murty SVS, Suresh-Kumar R, Mondal K (2013) "Effect of hot-rolling on the enhancement of mechanical properties of low density Cu-Cr-Nb sintered alloy. Mater Des 43:125–133
69. Shukla AK, Narayana-Murty SVS, Suresh Kumar R, Mondal K (2013) Enhancement of high temperature ductility of hot-pressed Cu–Cr–Nb alloy by hot rolling. Mater Sci Eng, A 577:36–42
70. Shukla K, Narayana Murty SVS, Suresh-Kumar R, Mondal K (2013) Spark Plasma sintering of dispersion hardened Cu-Cr-Nb alloy powders. J Alloy Compd 577:70–78
71. Doiphode RL, Narayana Murty SVS, Kashyap BP (2019) Hot Deformation characteristics of magnesium alloys in magnesium and its alloys: technology and applications. In: Leszec AD, Menachem B, George ET (eds) Magnesium and its alloys. CRC Press, Hoboken, pp 57–89
72. Nayan N, Gurao NP, Narayana-Murty SVS, Venkitakrishanan PV (2021) Plane strain compression of Nb-10Hf-1Ti alloy: effect on microstructure and micro-texture. Trans Indian Inst Met 74:957–968
73. Gupta RK, Anil-Kumar V, Karthikeyan MK, Ramkumar P, Ramesh-Narayanan P, Sinha PP (2010) Investigation of cracks generated in columbium alloy (C-103) sheets during deep drawing operation. J Fail Anal Prevent 10:228–232
74. Acharya SM, Govind AA, Sharma SC, Sreekumar K, Sinha PP (2012) Study of shell cracking behavior and its remedies in investment casting process using quick cast rapid prototype polymer patterns. Mater Sci Forum 710:214–219
75. Nimbalkar VM, Bhanushali B, Mohape M, Pandav SG, Deshmukh VP, Dineshraj S, Acharya M, Agarwal-Govind A, Sharma SC (2015) Development of thin walled A-356 components by new rheocasting semi-solid metal processing technology (NRC). Mater Sci Forum 830–831:27–29
76. Dineshraj S, Acharya M, Agarwal A, Girikumar S, Sharma GSC, George KM (2015) Development of hot isostatic pressing technology for investment cast products. Mater Sci Forum 830–831:19–22
77. Saravanan TT, Kamaraj M, Sharma SC, Kumaran S, Chakravadhanula VSK, Ravikanth KV, Kumar KV, Sreemoolanadhan H (2020) On characteristic eutectic free microstructural evolution in hyper electric Al-Si processed through spark plasma sintering. J. Materials Letters 275:128150
78. Paidpilli M, Upadhyay A, Khanra GP, Sharma SC (2018) Investigation of sintered properties on infiltrated tungsten-copper composite along the infiltration direction. Can Metall Q 57:120–128
79. Shukla AK, Nayan N, Murty SVSN, Sharma SC, Chandran P, Bakshi SR, George KM (2013) Processing of copper-carbon nanotube composites by vacuum hot pressing technique. Mater Sci Eng A 560:365–371
80. Shukla AK, Nayan N, Murty SVSN, Mondal K, Sharma SC, George KM, Bakshi SR (2013) Processing copper–carbon nanotube composite powders by high energy milling. Mater Character 84:58–66
81. Mishra DK, Saravanan TT, Khanra GP, Giri-Kumar S, Sharma SC, Sreekumar K, Sinha PP (2010) Studies on the processing of nickel base porous wicks for capillary

pumped loop for thermal management of space crafts. Adv Powder Technol 21:658–662
82. Sreemoolanadhan H, Masin B, Mathew M, Sharma SC (2015) Development of patch antenna substrate in BaO-4.TiO2 system. Mater Sci Forum 830–831:425–428
83. George J, Aanandan C, Mohanan P, Nair KD, Sreemoolanathan H, Sebastian M (1998) Dielectric resonator loaded microstrip antenna for enhanced impedence bandwidth and efficiency. Microw Opt Technol Lett 17:205–207
84. Venkateswaran C, Sreemoolanadhan H, Sharma SC, Pant B, Chauhan VS, Vaish R (2020) Processing of Li_2O-Al_2O_3-SiO_2 (LAS) glass ceramic with and without P_2O_5 through bulk and sintering routes. J Non-Cryst Solids 550:120289
85. Venkateswaran C, Sharma SC, Pant B, Chauhan VS, Vaish R (2019) Crystallisation studies on site saturated lithium aluminosilicate (LAS) glass. Thermochim Acta 679:178311
86. Venkateswaran C, Sharma SC, Chauhan VS, Vaish R (2018) Near-zero thermal expansion transparent lithium aluminosilicate glass ceramic by microwave hybrid treatment. J Am Ceram Soc 101:140–150
87. Venkateswaran C, Padala A, Sreemoolanadhan H, Ajith MR, Mathew M, Sharma SC (2015) Development of machinable glass-ceramic without nucleating agents. Mater Sci Forum 830–831:436–439
88. Ajith MR (2005) Synthesis and characterization of silica-silica porous composites and calcium strontium zirconium phosphate ceramics for thermal protection applications, Ph.D. thesis, Indian Institute of Science, Bangalore
89. Hasan MA, Dey A, Esther ACM, Maiti P, Mukhopadhyay AK, Rajendra A (2020) Structural, out-gassing and nanomechanical properties of super hydrophobic transparent silica aerogels developed by ambient pressure drying for space application. Bull Mater Sci 43:287
90. Hasan M, Sangashetty A, Esther R, Sharanabasappa ACM, Baburao BP, Arjun-Dey NS (2017) Prospect of thermal insulation by silica aerogel: a brief review. J Inst Eng India Ser D 98:297–304
91. Nagapriya S, Ajith MR, Sreemoolanadhan H, Sree-Nageswari VK, Simon-Wesley C, Sharma SC (2012) Hollow silica granules by microwave processing. Adv Mat Res 585:87–91
92. Sharma SC, Naidu NKR, Mittal MC, Lakshmanan TS, Sinha PP, Vaidyan VK (2009) Tailoring of density in carbon foams. I J Eng Mat Sci 16:56–60
93. Devasia R, Painuly A, Devapal D, Krishnan R (2021) Continuous fiber reinforced ceramic matrix composites in Fiber reinforced composites constituents, compatibility, perspectives and applications. Woodhead Publ Ser Compos Sci Eng 2021:669–751
94. Sasikala TS, Thomas D, Devapal D (2015) Studies on evolution of nano SiC ceramics from allyborosiloxane. Ceram Int 42:1618–1626
95. Nithin-Chandran BS, Devapal D, Prabhakaran PV (2019) Synthesis of zirconium diboride based ultra high temperature ceramics via pre-ceramic route. Ceram Int 45:25092–25096
96. Suresh-Kumar R, Shukla AK, Babu S, Sivakumar D, Gandhi AS (2011) Densification of silicon carbide using oxynitride additives for space-based telescope mirror applications. Optical Eng 50:070504
97. Pradeep PI, Akhilesh AM, Anil Kumar V, Manikandan P, Naresh Kumar K, Venkateswaran T, Sahu A, Singh SK (2021) Characterization of titanium alloy Ti6Al4V-ELI components made by laser powder bed fusion route for space applications. Trans INAE. https://doi.org/10.1007/s41403-021-00254-7
98. Jinoop AN, Paul CP, Ganesh Kumar J, Anil Kumar V, Singh R, Rao S, Bindra KS (2021) Influence of heat treatment on the microstructure evolution and elevated temperature mechanical properties of hastelloy-x processed by laser directed energy deposition. J Alloys Compd 868:159207
99. Pradeep PI, Anil-Kumar V, Sriranganath A, Singh SK, Sahu A, Sasi-Kumar T, Ramesh-Narayanan P, Arumugam M, Mohan M (2020) Characterization and qualification of LPBF additively manufactured AISI-316L stainless steel brackets for aerospace application. Trans INAE. https://doi.org/10.1007/s41403-020-00159-x

S. V. S. Narayana Murty has received his B.E. (Metallurgy) from Andhra University, Visakhapatnam (1991), M.E. (Metallurgy) from IISc-Bangalore (1993) and Ph.D. (Metallurgy) from IIT-Bombay (2003). He joined Vikram Sarabhai Space Centre (VSSC), Trivandrum in 1993 and has worked on materials processing, testing characterization of various grades of aerospace materials and failure analysis investigations of launch vehicle hardware. He was head of the Material Characterisation Division of Materials and Metallurgy Group at VSSC. He has extensively worked on the thermomechanical processing of a number of aerospace materials used in launch vehicles and satellites and established processing maps to obtain defect free products. Presently, he is the General Manager of Material Development and Production Group at Liquid Propulsion Systems Centre, Trivandrum. He has more than 250 international peer reviewed publications which include review articles, contributions to encyclopedias and handbooks. He is a recipient of Young Metallurgist Award (2001) and Metallurgist of the Year award (2018), both from Ministry of Steel, Government of India. He received NIMS post-doctoral fellowship from National Institute for Materials Science, Japan (2003-2006). He was a member of ISRO Team excellence award for "Indigenization of Copper alloy Cu-Cr-Ti-Zr thrust chamber of cryogenic and semi-cryogenic engines" (2012). He received AIDA Technology Innovation award by Japan Society for Technology of Plasticity (2009) for Development of Ultrafine Grained Steels. He is an elected fellow of the Andhra Pradesh Akademi of Sciences, (2017) and Indian National Academy of Engineering (2021). He is on the editorial boards of Transaction of the Indian Institute of Metals, (Springer), Encyclopedia of Aluminium alloys (Taylor and Francis), ASTM Journal of Materials Performance and Characterization. He is also a member of the American Society for Metals (ASM) Handbook committee. He is a life member of Indian Institute of Metals, Materials Research Society of India, Aeronautical Society of India, Astronautical Society of India, Society for Aerospace Manufacturing Engineers and a member of the ASM International.

Sharad Chandra Sharma obtained his B.E. (Metallurgy) from University of Roorkee, (presently IIT, Roorkee), M.S. (Materials Science & Engg.) from IISc., Bangalore and Ph.D. from Faculty of Science & Engg., University of Kerala. He joined Vikram Sarabhai Space Centre (VSSC) in 1982 and worked on physical metallurgy, heat treatment and welding of ultra-high strength Maraging steels, High Strength Low Alloy (HSLA) steels like 15CDV6, special grades of stainless steels and superalloys for Indian Space Programmes. He was Project Leader of the programme to develop special purpose alloys for Inertial Navigation Systems of launch vehicles and satellites. As Head, Materials Processing Division and later as Head, Special Materials Division, Dr. Sharma guided the development of powder metallurgy products, ferrous & non-ferrous alloys and complex investment castings for space applications. He was Group Director, Materials & Metallurgy Group and steered the materials development programme of ISRO including high temperature materials such Ceramic matrix composites, Ultra-high temperature ceramics, Thermal barrier coatings and ignition resistance coatings. He was Deputy Director, VSSC(PCM) and in this position, he led R&D and product development activities in the areas of Propellants, Polymers, Chemicals and Materials for various prestigious projects of ISRO. Presently Dr. Sharma is steering the entire research and development programme of VSSC as Associate Director, R&D, VSSC. He was a Visiting Scientist for about a year in German Aerospace Establishment, Cologne where he worked on 'non-equilibrium solidification of materials'. He has published 128 technical papers in national & international journals and has 8 patents to his credit. He is a recipient of many prestigious awards and honours which include "Metallurgist of the Year Award" of Ministry of Steel and Mines, Govt. of India, "Distinguished Alumnus Award" of Indian Institute of Technology, Roorkee, "ISRO Merit Award" for individual excellence in R&D for Indian space programme, "VASVIK Industrial Research Award". He has received "Certificate of Appreciation" from International Astronautical Federation (IAF) for outstanding contributions to the activities of IAF's Technical Committee on "Microgravity Sciences and Processes" as its Member. He is a Fellow of Indian National Academy of Engineering, Indian Institute of Metals and Indian Institute of Ceramics.